Hybrid Geosynthetic Solution for Rail Track on Expansive Clay

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ABSTRACT

Large areas around the globe consist of expansive weak clay subgrades. The subgrade volume of these clays change as a result of seasonal changes in moisture content. In unpaved rail track pavement structures swelling causes severe degradation of rail alignment leading to extensive maintenance efforts. One method to deal with this phenomenon is to create horizontal and vertical moisture barriers. Local experience in Israel however, indicates that only partial restraint of swell damages can be achieved by such barriers. The Israeli Rail Authority has recently adopted and implemented a "Hybrid Geosynthetic Solution" that effectively restrains differential heave caused by uneven swelling of the clay subgrade. The hybrid geosynthetic solution is comprised of a stiff biaxial geogrid located at the subgrade/pavement interface combined with a stiff geocell layer embedded in the unbound sub-ballast granular layer. The geocell material is made of novel polymeric alloy (NPA) capable of sustaining large hoop stresses with relatively small strains.

1.   INTRODUCTION

Expansive soils cover large areas of the state of Israel, where an estimated half of all new highways and railways located on expansive clay soils. Expansive clay soils undergo large amounts of heaving and shrinking due to seasonal moisture changes. These movements lead to cracking and buckling of infrastructure built on such soils, resulting in extensive damage. In the United States alone for example, the estimated annual cost of the damage to infrastructure built on expansive clay exceeds 9 billion dollars (Zhao et al 2014).

One way to deal with this phenomenon is to construct horizontal and vertical moisture barriers. Local experience with this method in Israel indicates that only partial restraint of swell damages can be achieved. Substantial field evidence of the Israel Rail Authority shows far from satisfactory performance of rail tracks constructed on expansive clay soils treated with moisture barriers, leading to excessive maintenance and significant costs.

Recent innovations in geocell technology resulted in the introduction of a geocell made from novel polymeric alloy (NPA). These geocells can sustain large hoop stresses with relatively small strains along the design period (Han et al 2011). As a result of this technological advancement new types of structural pavement solutions can be designed.

The newly developed Hybrid Geosynthetic Solution restrains expansive soil damage without maintaining the uniform moisture regime that moisture barriers should theoretically do. On the contrary, the new hybrid solution is almost unaffected when the underlying expansive soil subgrade moisture regime varies. The solution has been implemented by the Israeli Rail Authority to restrain differential heave caused to rail track pavements by the uneven swelling of expansive soil subgrade for a decade.

The Hybrid Geosynthetic Solution combines a stiff biaxial geogrid located at the subgrade/pavement interface with a stiff geocell layer embedded in the unbound granular layer. The geocell material is made of novel polymeric alloy (NPA) capable of maintaining large hoop stresses under relatively small strains. The Hybrid Geosynthetic Solution creates a unique composite behavior that exceeds the sum of its components. 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 unaffected by variable moisture in the expansive soil subgrade.

2.   CONVENTIONAL PRACTICE FOR EXPANSIVE CLAYS

The procedures of the Israel Rail Authority for restraining expansive clay subgrades include the following (Livneh 2013):

- Replacement of upper subgrade soil to a depth of 40-60 cm
- Placement of horizontal HDPE geomembrane across the entire width of pavement
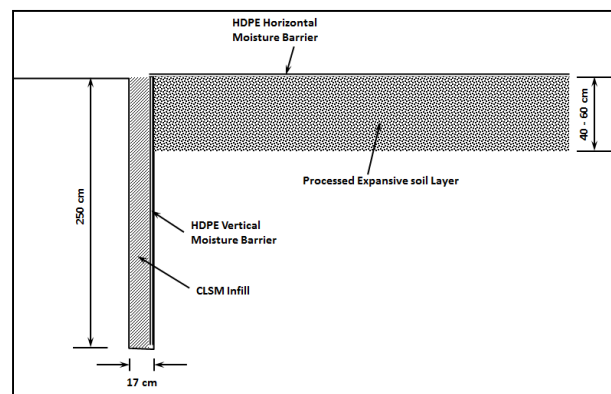

Figure 1. Moisture barrier typical cross section

- Installation of vertical HDPE geomembrane inside a trench 17 cm width to 250 cm depth infilled with Controlled Low-Strength Material (CLSM) (see Figure 1).

In order to reduce construction costs, specifications for the CLSM infill call for the lowest available requirements; for example, the requirement for permeability is 10^{-3} cm/sec (Israel National Roads Authority, 2003). Uniformly well graded coarse sand has a relatively high permeability with a coefficient of water conductivity of approximately 4.0 x 10^{-1} cm/sec. On the other hand, clay has a relatively low permeability with a coefficient of water conductivity of 1.0 x 10^{-7} cm/sec. Therefore, the CLSM infill is permeable in practice and thus neutralizes the original purpose – extension of the flow lines. In addition, as the installation process for HDPE geomembranes is sensitive to ambient temperatures, implementation is restricted to evening and/or early morning hours, a time when quality control is often lacking.

Even if the moisture barrier somehow fulfilled the role of isolating moisture migration in and out of the encapsulated expansive clay soil, it will tend to reach suction equilibrium. This trend causes swelling in the drier parts and contraction in the wetter parts. As clay has relatively low permeability, this process can take several years until suction equilibrium is reached inside the encapsulated zone. This phenomena was evidenced and monitored during several seasons on two test sites built by the Israeli National Roads Authority during the early 90's as shown in Figure 2 and Figure 3 (Kief et al 1995).
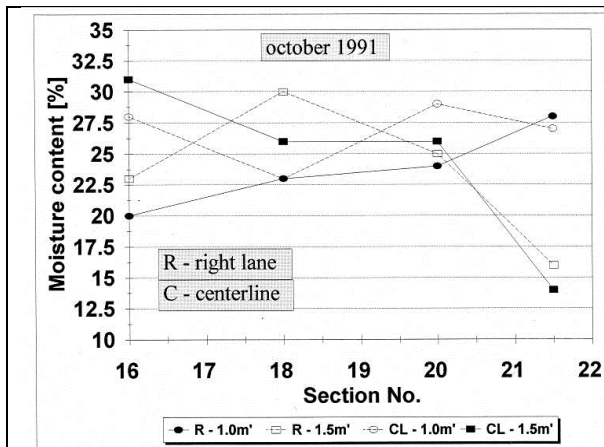

Figure 2: Moisture content variation along Road 65 test section, autumn 1991.
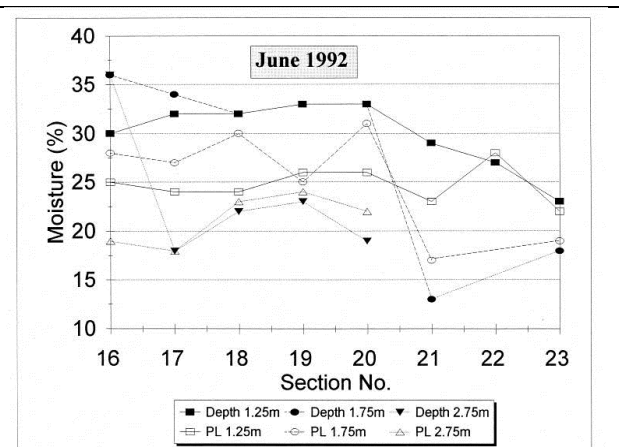

Figure 3: Moisture content variation along Road 65 test section, summer 1992.

This phenomenon can be explained through a numerical exercise for moisture deviation in Membrane Encapsulated Soil Layer system (Koerner 1990). Based on comprehensive research at several test sites in Texas followed up with numerous laboratory tests (Lytton et al 2004), it can be concluded that the contribution of vertical moisture barriers to a reduction in pavement roughness along the service period is negligible. In some cases this solution may actually cause the opposite effect. Since the effectiveness of the moisture barrier solution is questionable, not to say time consuming, a better restraining solution with structural capabilities is presented.

3. NAHARIYA ACRE RAILWAY LINE

3.1 General

The Nahariya-Acre Rail line is the Northern section of the Israeli Coastal Rail main line (Figure 4). In response to increased demand, the Israeli Railway Authority decided to double the existing single track. The Increased frequency would allow operation of three trains in each direction during peak hours (six trains per hour) compared with two trains in each direction today (four trains per hour).

The single Western Track between Acre to Nahariya was fully rehabilitated two years ago. Earthworks for a 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 specified of compaction. At this point, and as a result of unsatisfactory riding quality of the rehabilitated Western Track (excessive roughness), the Railway Authority decided to implement a Hybrid Geosynthetic Solution for the new Eastern Track.
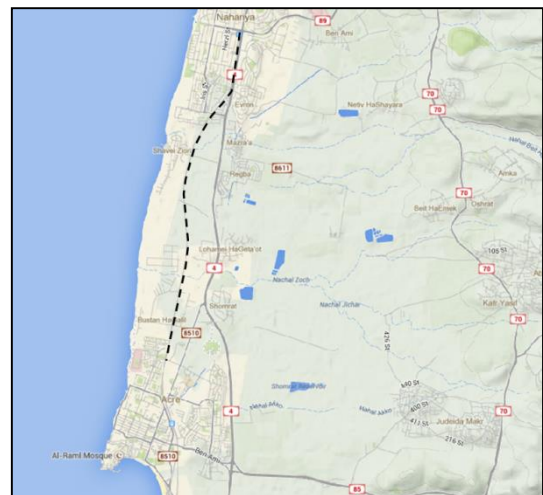

Figure 4. Location of Nahariya - Acre Rail Line

3.2   GEOTECHNICAL DATA

A comprehensive soil exploration along the track route was performed during the winter of 2003. The natural subgrade is characterized as one unit type alluvial clay soil classified 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) conducted along the track route. The results from those tests were converted using local available correlations to CBR values. 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

For the 85 percentile the design CBR value is 2.8%. For the 90 percentile the design CBR value is 1.5%. The design CBR value adopted for the structural calculation was 2.0%.

3.3   CLIMATIC DATA

The Northern coastline of Israel where the railway route is located is categorized as Mediterranean climate. The average annual precipitation for Nahariya is 640 mm, which classifies it as Semi-Arid. This climatic subgroup is characterized by long dry periods with high rainfall in short periods. These are the perfect conditions to magnify damage resulting from subgrade volume changes.

3.4   CONVENTIONAL DESIGN

The fully rehabilitated Western Track was constructed according to the Israel *Design Guidelines for Upper and Lower Railway Structures* (Livneh 2003). According to the conventional design guidelines the track category for a major line with a design speed of 160 km/hr is Category 3. The conventional pavement structure 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

3.5   METHODOLOGY OF PAVEMENT COMPARISON

The principles of structural pavement comparison are based herein on the applied vertical stress on the subgrade surface due to the static applied load of the train axles loads. Load transfer works on the principle of stress reduction, which means layer by layer, as depicted schematically in Figure 5 (Esveld, 2001).
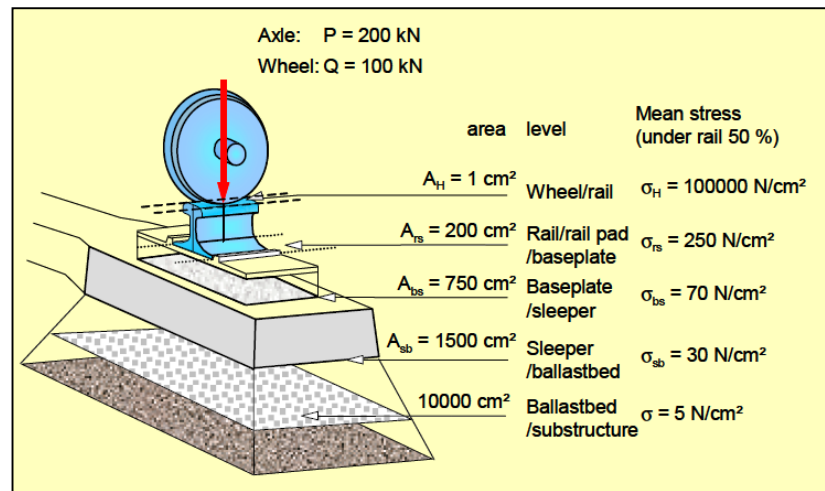

Figure 5. Principle of Load Transfer in Track Structure Layers

In order to suggest a structural alternative the maximal vertical stress acting on the subgrade surface should be equal or lower than the one applied by the conventional solution. It can be derived from Figure 5 that the vertical stress (σ_{zz}) applied on the ballast bed / sub-ballast interface for an axle weight of 200 kN is 5 N/cm^2 (50 kPa). In order to use an axis-symmetric stress analysis the applied stresses on a rectangle area of 10,000 cm^2 were transformed to a circle pattern with a radius of 564 mm of the same area. The elastic moduli of the different pavement layers are listed in the table below:

Table 3. Elastic Modulus of Pavement Layers – Conventional Solution

	Elasticity Parameters	Notes
Sub-ballast	$E_{sb} = E_{sg}$ x (1+0.003 x h_{sb} [mm]) $\upsilon_{sb} = 0.35$	E_{sb} [MPa] $\leq$ 300
Subgrade	E_{sg} [MPa] = 14 x CBR [%] $\upsilon_{sg} = 0.40$	2 < CBR [%] < 12

Where:

h_{sub}	-	Sub-ballast layer thickness [mm]
E_{sg}	-	Subgrade elastic modulus [MPa]
E_{sub}	-	Sub-ballast 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 750) = 91 MPa

The graphical presentation of the conventional solution for the Western Track is illustrated below:
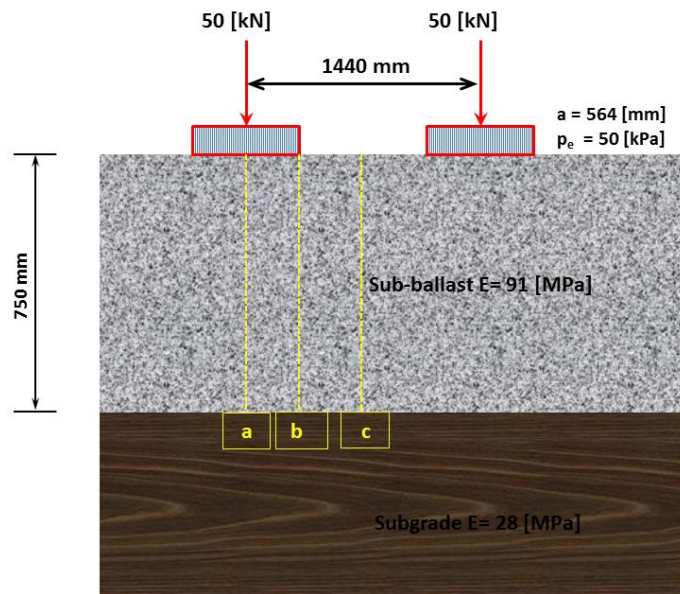

Figure 7. Western Track Conventional Pavement Structure

The vertical settlement on the sub-ballast surface and the vertical stress on the subgrade surface were calculated in three points using stress/strain software. The results are listed in table 4 below:

Table 4. Settlement and Stress – Three Points: Conventional Solution

Sub-ballast Surface Settlement [mm]			Subgrade Surface Vertical Stress (σ_{zz}) [kPa]		
Point a	Point b	Point c	Point a	Point b	Point c
1.11	1.14	0.98	19.1	18.8	16.6

The maximal sub-ballast surface vertical settlement is 1.1 mm.
The maximal subgrade surface vertical stress (σ_{zz}) is 19.1 kPa.

4.   HYBRID GEOSYNTHETIC DESIGN FOR THE NEW EASTERN TRACK

4.1   General

The soil exploration survey results present the designer with two major geotechnical problems: 1) Subgrade with low CBR value (bearing capacity problem) and 2) Subgrade subject to volumetric changes (swelling of expansive clay).

Several railway sections in Israel were successfully constructed on expansive clay subgrades in the past few years utilizing the Hybrid Geosynthetic Solution. This solution combines a stiff biaxial geogrid located at the subgrade/pavement interface and one and/or more stiff geocell layers embedded in the unbound granular layers. The geocell material is made of novel polymeric alloy (NPA) capable of withstanding large hoop stresses with relatively small strains.

The structural performance and rail alignment of track with the Hybrid Geosynthetic Solution has proven to be quite satisfactory, leading the Israel Rail Authority to adopt the solution for all problematic soil conditions. Within this framework, the Rail Authority decided to construct the new Eastern Track using the Hybrid Geosynthetic Solution.

4.2   Initial Geotechnical Earthwork Conditions (See Figure 6)

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.

Figure 6. Geotechnical Conditions Eastern Track

The initial earthwork conditions as described above led to the decision to implement the Hybrid Geosynthetic Solution. Moreover, this solution enabled the Rail Authority to maintain live service on the Western Track while constructing the adjacent new Eastern Track.

4.3   Engineering Considerations

The Hybrid Geosynthetic Solution was utilized to address two major geotechnical problems: the low bearing capacity and the volumetric changes (swelling of expansive clay). The deployment of stiff novel polymeric alloy (NPA) geocells directly over weak strata is more effective with a stable working platform. This provides a counter force to the compaction forces during the geocell infilling process, while preventing the infill from breaking out into the weak subgrade.

The use of a stiff biaxial geogrid on the smoothed subgrade surface achieved the following benefits:
- Create a working platform on the weak subgrade.
- Wider distribution and reduced vertical stresses transferred into the subgrade (Han, et al 2013).
- Interlocking mechanism of granular material inside the geogrid aperture will restrain subgrade contraction cracks from reflecting into the pavement structure (Zornberg 2010).

By using two layers of NPA geocells the following benefits can be achieved:
- Create a relatively high modulus, confined granular layer, which acts as a 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 integrated benefits of the Hybrid Geosynthetic Solution create a unique composite pavement, ideally suited to restrain the swelling process. By creating a semi-rigid platform the differential heave resulting from the volumetric change is almost completely reduced. The surface roughness, caused by the volumetric change, is sawtooth-shaped in nature as a result of the differential heave. It can be described as waves with short amplitude. The assumption is that the effect of the unique composite semi-rigid platform generates smoothened surface be extending the swell amplitude.

4.4   Implementation of the Hybrid Geosynthetic Solution

In light of the initial earthwork conditions and the impact on the construction timetable the following design changes were implemented:
   a. The existing excavation level was set as the lower reference point for the track pavement structure.
   b. Subgrade process operations were discontinued, aside from surface smoothing operations and watering to avoid excessive drying.
   c. The stiff biaxial geogrid was installed on the entire excavated section and covered with sub-ballast material.
   d. Two layers of NPA geocells were installed, including laying out the sections, infilling with sub-ballast material, grading and compaction for each one of the layers.

The "constraints" listed above led to the unique pavement structure of the 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 Geogrid
- Smoothed Subgrade

4.5   Hybrid Geosynthetic Solution Structural Assessment

Based upon numerous laboratory and field tests worldwide a Modulus Improvement Factor (MIF) for NPA geocell confined granular layers was established (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 factor of approximately 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 approximately 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 7):
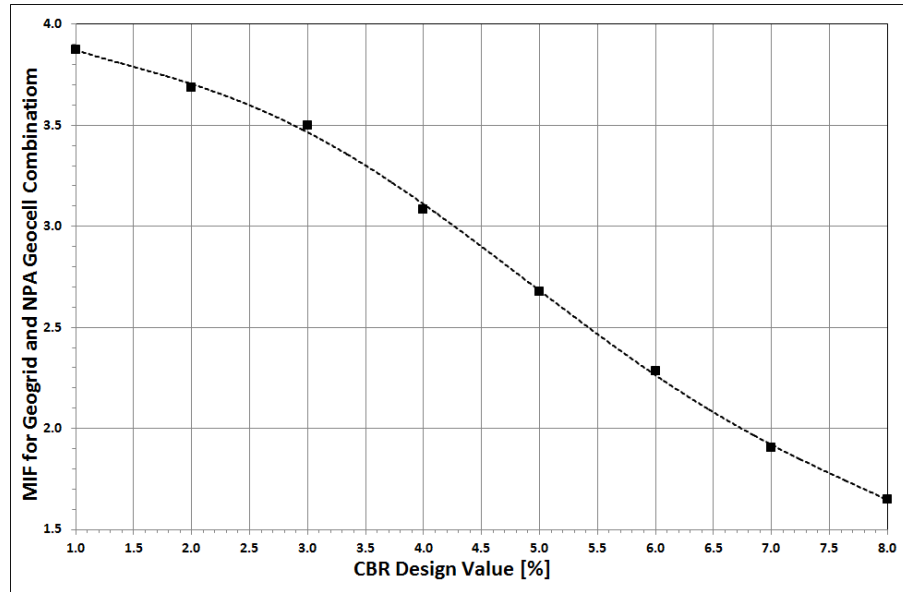
Figure 7. MIF Value vs. CBR Value

For the current project a MIF value of 3.7 was set for design CBR value of 2.0%.
The 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 750) x 3.7 = 337 MPa.

The cross section view of the Hybrid Geosynthetic Solution (Eastern Track) is illustrated in Figure 8:
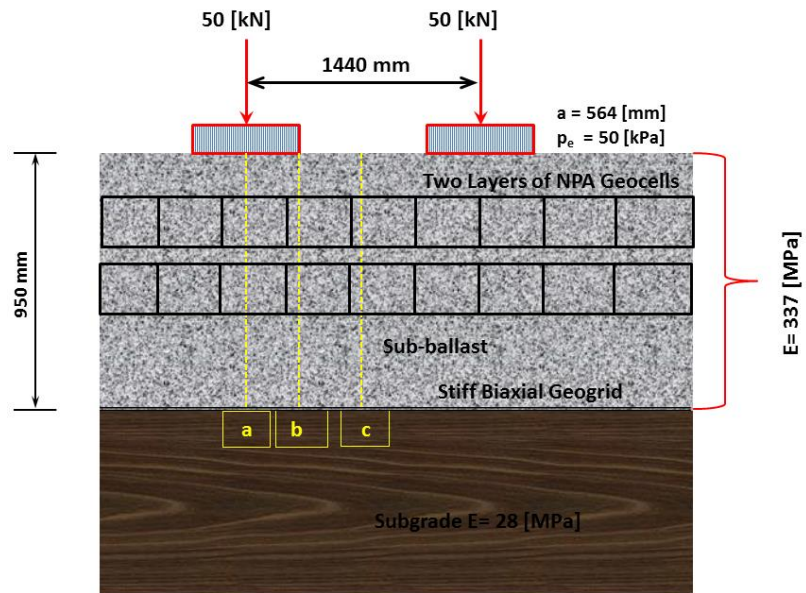

Figure 8. Cross Section of Hybrid Geosynthetic Solution for the Eastern Track

The vertical settlement on the sub-ballast surface and the vertical stress on the subgrade surface were calculated in three points using stress/strain software. The results are listed in the table below:

Table 5. Settlement and Stress – 3 Points: Hybrid Geosynthetic Solution

Sub-ballast Surface Settlement [mm]			Subgrade Surface Vertical Stress (σ_{zz}) [kPa]		
Point a	Point b	Point c	Point a	Point b	Point c
0.60	0.62	0.59	8.6	8.9	8.7

The maximal sub-ballast surface vertical settlement is 0.6 mm. The maximal calculated subgrade surface vertical stress (σ_{zz}) is 8.9 kPa before taking into account the stress reduction effect of the NPA geocell layers. 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

If P denotes the load per axle and T denotes the daily traffic tonnage the equation above becomes:

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{T_2 / P_2}{T_1 / P_1} \right)^{\lambda}$$

For constant axle loads, P1 = P2 and the 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:

$$\frac{\sigma_{zz1}}{\sigma_{zz2}} = \frac{19.1}{8.9} = \left(\frac{T_2}{T_1} \right)^{\lambda} = 2.14$$

$$\left(\frac{T_2}{T_1} \right) = 45.5$$

It can be concluded from the above equations 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 successive maintenance operations for the new Eastern Track will be significantly extended compared to the conventional Western Track.

5. MONITORING SETTLEMENTS

The Israeli Railway Authority monitors the track conditions routinely. At least once every two months, a track survey car monitors the track geometry. The best indication regarding the volumetric activity of the expansive clay is achieved by measuring the vertical settlement and/or vertical heave of the two rail heads periodically.

The Eastern Track, as new track, first had to undergo a cumulative tonnage of 100,000 gross tons before profile monitoring. The chart in Figure 9 illustrates the vertical settlement and/or vertical heave measured along the conventional Western Track only. It should be noted there is no chart for the Eastern Track, as no vertical settlement and/or vertical heave have yet been recorded along the new track with the Hybrid Geosynthetic Solution.
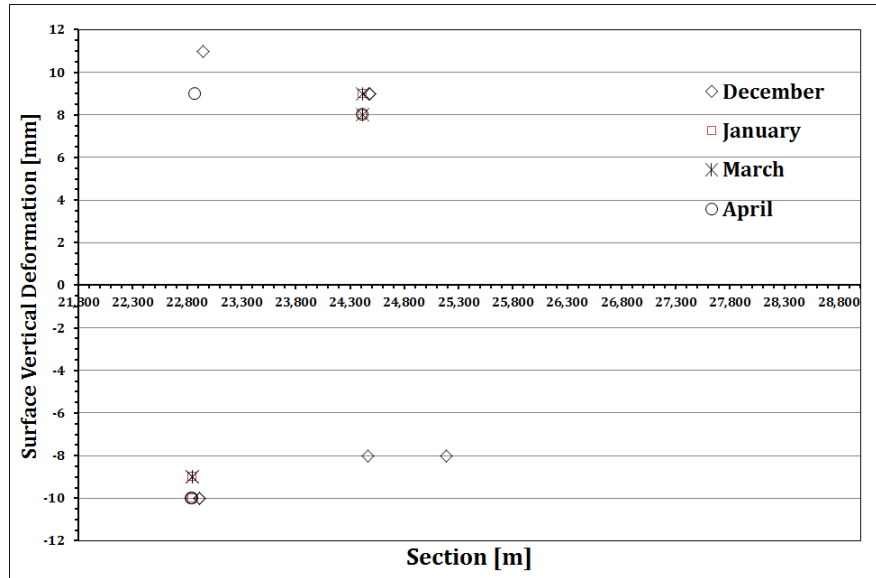
Figure 9. Western (Conventional) Track Surface Deformation

As mentioned before the climatic zone along the track route is defined as semi-arid. The graph in Figure 10 depicts the average monthly precipitation compared to the recorded Nahariya station precipitation for 2013/2014.

It can be clearly seen that long period of drought in autumn 2013 was followed with unusually high precipitation during December 2013. This should have triggered the volumetric change potential of the clay subgrade under the newly built Eastern Track. The ongoing longitudinal rail heads measurements prove that Hybrid Geosynthetic Solution is more than a suitable solution for rail tracks over expansive clay subgrades.
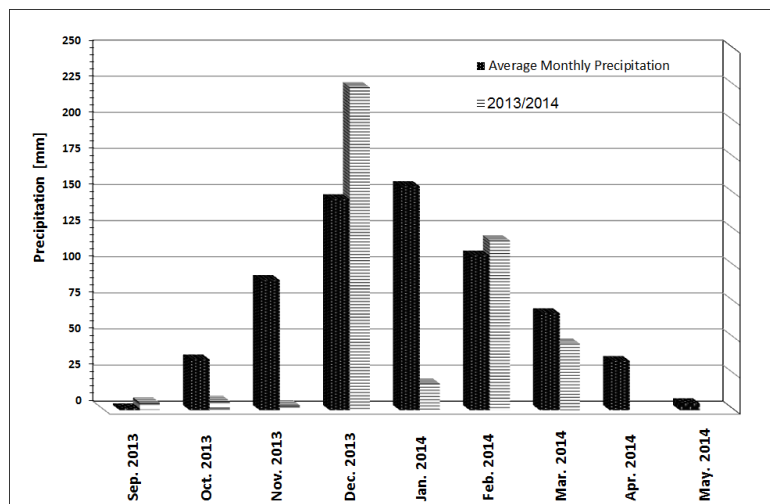

Figure 10. Average Monthly Precipitation

6. 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 geogrid layer at the clay subgrade with a geocell layer that reinforces the sub-ballast layer. The stiff 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. The effectiveness of the solution was verified by track monitoring measurements which have demonstrated negligible rail head settlements compared to an adjacent 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

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