FIRST TIME APPLICATION OF EXPANDED POLYSTYRENE IN HIGHWAY PROJECTS IN GREECE

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central Greece
south of Maliakos Gulf
and the city of Lamia

Athens-Thessaloniki
E75 major highway

length: 1km
$H_{\text{max}}$ embankment: 8.5m

period: summer 2008
adjacent to historical site of the battle of Thermopylae (480 B.C.)
Leonidas, king of Sparta + 300 warriors hindered Persian invasion to Europe

battle 480 B.C. : narrow passage between the sea and the mountains
recent marine and deltaic deposits
- plain and swampy area
- GL ≈+1.0m
- GWL = 0 (surface)
- very poor ground properties

7.5m highway embankment / underpass of local road and culverts
8.5m approach embankment for Thermopylae I/C branch overpass replacement
1m / stone columns D=80cm, L=11-15m, s=3m
height of $4 \div 4,5m \rightarrow$ global failure $l = 200m$

continuous $\geq 2m$ wide rupture // alignment, $\approx 10 \div 14m$ from edge

outer part subsided $\approx 1m$
GROUND CONDITIONS AND FAILURE ANALYSIS

Investigation:
• boreholes
• trial pits
• deformation recordings
• back analysis

very soft Clay (CH), $z = 10 \div 12m$
compressible, NC clayey deposits, $z \approx 25m$
deep seated, undrained failure of very soft clay (A), depth 5-10m

soil resistance overestimated, back analysis -> $Su = 12\text{kPa}$

stone columns negligible contribution, limited side support

reduced diameter ($D=0.5\div0.6\text{m}$), inferior quality with depth ($\phi=32^\circ$)

SC at failure: highly mixed with clay, distinct rupture at depth $\sim3\div5\text{m}$
long term consolidation settlements (layers A,B, z=25m)

Evaluation:
• GI data
• pre-failure settlement recordings
• long term monitoring of neighboring railway project

\[
\begin{align*}
\text{max settlement} &\approx 1.5m / 20\% H \\
\text{Slow: } 20\% - 25\% &\text{ during construction, } U_{1\text{yr}} \approx 50\%, > 10 \text{ years } \rightarrow U \approx 100\%
\end{align*}
\]
SELECTION OF A SOLUTION SATISFYING THE PROJECT’S REQUIREMENTS

- Stability - safe foundation, 10m very soft clay (F.S. ≥ 1.20 short term)
- PC settlement ≤10cm (Greek guidelines for highways)
- Rapid completion, serious traffic problems, political and social impact

removing Underpass => highway embankment ≤4.5m / IC branch 8.5m

Comparison of alternative solutions (only for the highway section)

<table>
<thead>
<tr>
<th>Solution</th>
<th>Constr. time</th>
<th>Cost (€)</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preloading, PVD, berms, stage</td>
<td>9 months (incl.preload)</td>
<td>3.6 M</td>
<td>Cost, experience</td>
<td>Time, uncertainties, expropriation, installation</td>
</tr>
<tr>
<td>construction.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stone columns l=20m, s=1,5m</td>
<td>&gt; 1 year (incl.preload)</td>
<td>10.6 M</td>
<td>-</td>
<td>Cost, time, reliability of SC, maintenance</td>
</tr>
<tr>
<td>Deep mixing l=10m, PVD l=25m</td>
<td>&gt; 9 months (incl.preload)</td>
<td>6.2 M</td>
<td>-</td>
<td>Cost, time, success depended on ground</td>
</tr>
<tr>
<td>EPS fill</td>
<td>2 months</td>
<td>5.8 M</td>
<td>Time, maintenance, unrelated to subsoil</td>
<td>Cost, lack of experience</td>
</tr>
</tbody>
</table>

much higher branch embankment - EPS solution the only realistic

authorities overcome concern about strength, durability and sustainability to hazards like fire, water absorption, oil spill, attack by rats
eliminate restrictions imposed by a heavy earth embankment, steep one way cross slope of the road surface (≈5%) into account
Complete removal of existing fill and top soil to depth 0.75m

Restriction of base layers to ≥50cm:
  a) 25cm selected material working platform,
  b) separation geotextile and tensile reinforcement geogrid
c) drainage-foundation and leveling granular layer varying thickness: 25cm - 75cm slightly inclined roof oriented parallel to road surface
Lightweight fill on top of the inclined leveling surface:
EPS 100 blocks
$B_{\text{min}} \times L_{\text{min}} = 1.0 \times 2.0 \text{m}$, layers $\geq 50 \text{cm}$, stepped side slope
LIGHTWEIGHT FILL DESIGN

- Consecutive layers at right angles to each other to avoid continuous vertical joints, upper row aligned transversal to the axis direction.
- Steel fasteners prevent blocks from moving out of position during the construction process.
✓ Side slopes:

• 1mm PE membrane
• Geotextile cloth
• ≈0.5m lightly compacted fine granular soil
• Slope 2:3 (v:h)
• 0.3m top soil.
15cm lightly reinforced concrete slab C20/25 on top of EPS fill → protection of fill crown against solvents, pavement’s proper foundation and drainage.
Pavement as determined by the original design:

- 22cm asphalt layers
- 40cm granular base layer,
- >15cm foundation and drainage layer on top of inclined slab
### MATERIAL REQUIREMENTS

#### Standards:
- European Standard EN 14933, “Thermal insulation and Light Weight fill products for Civil Engineering applications - Factory made products of Expanded Polystyrene (EPS)”

#### EPS 100 RF

<table>
<thead>
<tr>
<th>Description</th>
<th>Test method</th>
<th>Symbol - unit</th>
<th>Requirement</th>
<th>Tolerance</th>
<th>Control frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>EN 822-3</td>
<td>LxWxT (m)</td>
<td>$\geq 2.0 \times 1.0 \times 0.5$</td>
<td>0.5%</td>
<td>every 50 blocks</td>
</tr>
<tr>
<td>Squareness</td>
<td>EN 824</td>
<td>$(x,y,z)$</td>
<td>3mm/ 500mm length</td>
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<td></td>
</tr>
<tr>
<td>Evenness</td>
<td>EN 825</td>
<td>$(d/L)$</td>
<td>10mm/ 3m or 5mm / consecutive blocks</td>
<td></td>
<td>Cross section every 10m</td>
</tr>
<tr>
<td>Unit Density</td>
<td>EN 1602</td>
<td>$\rho$ (kg/m³)</td>
<td>20</td>
<td></td>
<td>every 1000m³</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>EN 826</td>
<td>$\sigma_{c10}$ (kPa)</td>
<td>$\geq 100$</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma_{c2}$ (kPa)</td>
<td>$\geq 50$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending strength</td>
<td>EN12089</td>
<td>$\sigma_b$ (kPa)</td>
<td>$\geq 150$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$W_{dv} \leq 5\%$, Flame-retardant Euroclass B (EN13501-1)
External Stability

**Cases:** Undrained, long term effective stress analysis, earthquake loading

**Method – Standards:** Bishop’s slices, Greek Seismic Code

**Software:** SLIDE

**Considerations:**

\[ \text{Su}_{\text{EPS}} = 100\text{kPa}, \ \gamma_{\text{EPS}} = 0.5 \text{ kN/m}^3 \]

F.S. = 4.3 compared to 0.73 earth embankment

\( H_{\text{MAX}} = 8.5\text{m} \) /critical undrained – deep seated
Soil Settlements

*Cases:* Total, long term consolidation, post construction

**Method - Analysis:** 2D Plane strain, Consolidation theory

**Software:** FOSSA

**Considerations:**
preloading by $h = 1 \div 1.5$ m earthfill

$\gamma_{\text{earthfill}} = 20 \text{ kN/m}^3$, $\gamma_{\text{EPS}} = 0.5 \text{ kN/m}^3$

$s_{pc} = 5\text{ cm}$ compared to 1.5m earth embankment ($H_{\text{MAX}} = 8.5\text{ m}$)
Buoyancy - uplift


**Cases:**
- **Global stability:** \[ F.S. = \{W_P + W_{sl} + W_{eps}\}/A > 1.3 \]
- **Local slope uplift:** \[ F.S. = (\gamma H_{sl})/[(\gamma w) \times (D+H_{WL})] > 1.2 \]

**Considerations:**
- \( \gamma_{EPS} = 0.2 \text{kN/m}^3 \)
- \( H_{WL} = \text{maximum probable water level above GL} = 1.0 \text{m} \)
- \( D = \text{maximum depth of EPS below GL} = 0.25 \text{m} \)

(Protection side ditches, drainage layers, construction in summer)

- Uplift during construction and transition due to an unbalanced water pressure not considered as potential risks
- Uplift due to wind forces omitted, due to lack of consistent methodology and reporting of relevant problems
Stresses and deformations in EPS

**Cases:**

a. Permanent loads on top of EPS (pavement and concrete slab) \( p = 20-25\, \text{kPa} \) =>
   - \( p < 30\% \) \( \sigma_{c10} = 30\, \text{kPa} \) (Frydenlund, Aaboe, 2001)
   - \( \varepsilon_i < 1\% \) immediate strain (NCHRP65, 2004)

b. Elastic, immediate deformation (during construction)
   
   \[ s_{\text{EPS}} = \frac{p \times H_{\text{EPS}}}{E_{\text{EPS}}} \]  
   \( E_{\text{EPS}} = 5\, \text{MPa} \) (TRB) => \( s_{\text{EPS}} \leq 20 \times 8/5000 = 1.3\, \text{cm} \)

   negligible compared to subsoil settlement

c. Deformations under repetitive traffic loads \( (q) \) on top of EPS

   load distribution:
   - pavement \( I_p = 1 \), \( T_{p,\text{min}} = 0.77\, \text{m} \)
   - concrete slab \( I_c = 2 \), \( T_c = 0.15\, \text{cm} \)

   =>

   \( q \leq 15.5\, \text{kPa} \ll 0.35\, \sigma_{c10} \)

   \( q+p \approx 35\, \text{kPa} < \sigma_e = 50\, \text{kPa} \) = minimum elastic limit stress (NCHRP)
Internal stability
Sliding between two consecutive EPS layers at top (min friction, max seismic action)

Method – Standards: NCHRP 65, Greek Seismic Code

Cases:
static (due to inclined layers): $F.S.s = \frac{W_p \times \tan(\delta)}{W_t} \geq 2.0$
wind force: $F.S.w = \frac{W_p \times b \times \tan(\delta)}{(P_xh + W_t x b)} \geq 1.2$
seismic: $F.S.e = \frac{[W_p - E_h \sin(\alpha) - E_v \cos(\alpha)] \times b \times \tan(\delta)}{(W_t + E_h \cos(\alpha) + E_v \cos(\alpha))} \geq 1.0$

Considerations:
$\delta = 30^\circ$, $\alpha =$ inclination (cross slope) of layers $= 3.15^\circ$

Pavement Design
- Conservative approach / first application of EPS fill
- Original pavement scheme for the earth embankment, CBR=3, disregarding concrete slab

no further check required
CONSTRUCTION DATA

 ✓ Application length: **1030m**
 ✓ EPS volume: **65,000m³**
 ✓ Construction time: **2.5 months (06-08/2008)**
 ✓ Inaugurated – opened to traffic: **18/09/08**
 ✓ Production rate: **1000m³/day**
   (including protection measures and quality control)
CONSTRUCTION DATA

- **Owner**: Greek State, Ministry of Public Works, Highway PATHE
- **Contractor**: ATTIKAT S.A.
- **Design**: Sotiropoulos & Associates SA
- **Technical experts**: K. Flaate, T.E. Frydenlund and A. Sagbakken, f. Norwegian Public Roads Administration

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"National Road by ... geofoam!"

Swampy ground directed engineers to new technologies

"Floating Highway"

"Solution from the Netherlands"

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Rapid and successful application → impressed the relevant authorities and the press
block dimensions adapted to production availability and construction acceleration (L = 3÷5m, B = 1.0÷1.35m, H = 0.6÷1.0m) thicker blocks at the upper layer

application design noted block types at every layer

minimum of 2 layers (except edge sections)

rearrangement to avoid transverse joints, adjustments to block lengths, shorter blocks to the inner side

blocks adjusted at junctions or adjacent to structures by an electric wire cutting

random gaps adjacent to structures filled by polyurethane foam - sealing membrane fixed on EPS

observed curvature → longitudinal wooden beams beneath the bottom block at the factory
Production plant (automatic and manual) / independent laboratory

EN14933: compressive strength control at 3 strain levels: 2 %, 5 % and 10 %

50mm cubic samples, 3 measurements for each test result, specimens from inner and the outer areas

Full compliance of the design requirements:

\[ \sigma_{c10} \approx 112 \text{ to } 121kPa > 100kPa, \sigma_{c2} > 50kPa, \sigma_{c5} \approx 0.9\sigma_{c10} \approx 100kPa, \text{ linear behavior up to 4\% strain}, \rho = 20.3 \div 21.2 \text{ kg/m}^3, \sigma_b = 200 \div 250 \gg 150kPa \]
QUALITY CONTROL AND MONITORING

11 benchmarks on top of EPS, every 100÷150m
Measurements at weekly basis
Post construction Settlements: uniform, ≈ 1cm << design prediction
(stiffer soil behavior at small strains)
QUALITY CONTROL AND MONITORING

EPS 3 months PC settlements much lower than neighboring sections:
- earth fill 4m and 7m
- stone columns
- better ground conditions

↓
EPS solution’s superiority in terms of time and maintenance.

3 years after completion very satisfactory performance, best among highway sections in the valley area - no settlements or other problems
CONCLUSIONS

✓ The first application of lightweight fill by expanded polystyrene in Greece was realized in an extended area with very poor ground conditions, in order to face important foundation problems, to overcome observed failures and to comply with project’s time schedule.

✓ Construction of embankments up to 8.5m by the use of a substantial EPS amount proved very successful in terms of safety, construction time and overall post construction performance after 3 years.

✓ The effectiveness of this first application, despite initial controversy and hesitations about the solution and the use of EPS in highway projects in general, honored a positive reputation to the project and the material. EPS became quite attractive to designers, contractors and many authorities for future application in road embankments and even more in bridge abutments.
Tusen Takk!

Thank you for your attention!

Ευχαριστώ πολύ!