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# General Report TC202 Transportation Geotechnics

## Rapport général du TC202 Géotechnique pour les infrastructures de transport

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**ABSTRACT:** Today's needs of urban transportation including roads, railways, airports and harbours demand significant resources for infrastructure development in view of rapid and efficient public and commercial (freight) services. In most cases, authorities have had difficulties in meeting these service demands due to the rapidly growing public, industrial, mining and agricultural sectors in many parts of the world. In order to maximise efficiency and to reduce the costs of maintenance, sound technical knowledge is required. This general report presents major technical advancements around the globe encompassing 33 articles from 19 countries and it is classified into 6 key categories, namely: compaction and subgrade improvement, laboratory testing, theoretical advancements and contributions to design, applications of geosynthetics, numerical modelling and field performance evaluation.

**KEYWORDS:** urban transportation, compaction, design, geosynthetics.

**RÉSUMÉ :** De nos jours, les besoins en transports urbains (routes, chemins de fer, aéroports aériens et maritimes) nécessitent d'importantes ressources pour le développement des infrastructures en vue d'assurer des services commerciaux rapides et efficaces. Dans la plupart des cas, en raison de la croissance rapide des secteurs public, industriel, minier et agricole, les autorités se trouvent confrontées à des difficultés pour atteindre les services escomptés. Un savoir technique est alors nécessaire en vue de maximiser l'efficacité et de réduire le coût d'entretien. Le présent rapport général expose les avancées techniques majeures à travers le monde synthétisant 33 articles émanant de 19 pays ; six thèmes clés sont classés : compactage et amélioration des assises, expérimentation en laboratoire, développements théoriques et contributions au dimensionnement, applications des géosynthétiques, modélisations numériques et évaluation des performances sur le terrain.

**Mots clés :** Transports urbains, compactage, dimensionnement, géosynthétiques.

### 1 INTRODUCTION

Modes of transportation including roads, railways, airports and harbours demand the most essential infrastructure in industrialised countries. While almost 90% of the population depends on public transport every day in many developing nations, in large developed countries such as Australia, the mining and agricultural sectors almost entirely depend on the efficient roads and rail services. Geotechnical aspects of infrastructure design and construction play an important role and face key challenges in optimising the performance of road pavements, rail tracks, runways and ports, as well as their maintenance throughout their operational life cycle. Maximising efficiency with acceptable longevity and ensuring the minimum cost of maintenance requires sound technical knowhow, implementation of new and appropriate technologies and effective administration of strategic public policies and investments. In essence, the key phases of transport geotechnics can be primarily categorised to general soil and rock mechanics applications in design, development of theoretical concepts and analysis, construction innovations, challenges and in-situ quality control, ground improvement schemes including compaction and problematic soil remediation, field performance monitoring and data interpretation, laboratory techniques and physical modelling, numerical simulation for design and performance verification, constitutive modelling of pavement materials, conventional in-situ testing and non-destructive techniques for foundations, risk assessment and failure prediction, among other topics.

TC202 (Transportation) of ISSMGE fosters the relevant challenges through an active cohort of international membership, and through an array of meetings, workshops and conferences disseminates the new ideas, technical concepts and innovative technologies to the worldwide geotechnical community. The 18th ICSMGE (Paris) has attracted about 33 articles from 19 countries in the area of Transportation. These papers cover the entire domain of transportation, but for the purpose of this General Report, they can be predominantly classified under the following 6 categories:

- a) Compaction and subgrade improvement
- b) Laboratory testing
- c) Theoretical advancements and contributions to design
- d) Applications of geosynthetics
- e) Numerical modelling
- f) Field performance evaluation

### 2 COMPACTION AND SUBGRADE IMPROVEMENT FOR TRANSPORT INFRASTRUCTURE

There are 5 articles included in this section. Two papers discuss the salient aspects related to the application of novel techniques in field compaction (Adam et al. 2013, Kuo et al. 2013) while one article focuses on the site evaluation of the compaction quality using an array of different instruments (Conde et al. 2013). Useful practical information related to the application of ground improvement methods in a brown coal landfill site (Kirstein et al. 2013) and laboratory characterization of cement

aggregates (Fonseca et al. 2013) applied to transport infrastructure are also presented and discussed.

Adam et al. (2013) introduced a finite element modeling framework for analyzing the performance and efficiency of an impact compactor in relation to the surface velocity, weight of impact compactor and number of passes. Field observations indicate that the impact compactor is suitable for treating a wide variety of loose soils and fills, but the effective treatment depth is dictated by the grain size, typically ranging from 4.5m to 10m depth. Experience of two case studies suggests that Dynamic Probing Tests (Figure 1) are adequate for evaluating the efficiency of compaction.

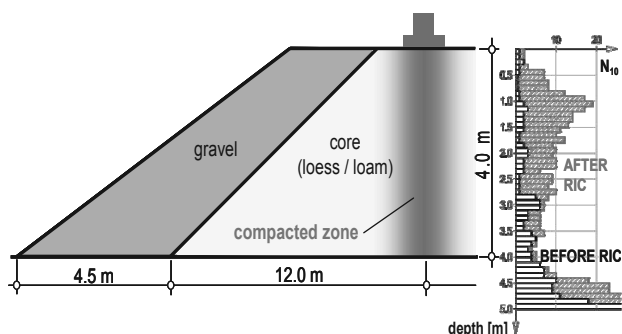


Figure 1. Test dike and correspondent dynamic probing test results. (Source: Fig 8, Adam et al. 2013).

Kuo et al. (2013) have described the effectiveness of Rolling Dynamic Compaction (RDC) by the combination of field studies with numerical modeling (Figure 2). At the ground surface, there are noticeable large deformations, and RDC proves to be most effective between the depths of 0.8m and 3.0m. The preliminary parametric study showed that most significant factors were soil cohesion, Poisson's ratio and shear modulus, as well as the width and mass of the RDC module.

An interesting study on the feasibility of a stiffness-based specification for embankment soil compaction quality control is discussed by Conde et al. (2013). An array of instruments are adopted for compaction control, which measures soil stiffness and then discussed on the basis of an earth dam construction. Among the different equipment used, the DCP (dynamic cone penetrometer) equipment showed greater promise as a compaction control tool, partly attributed to the strong negative correlation with water content values.

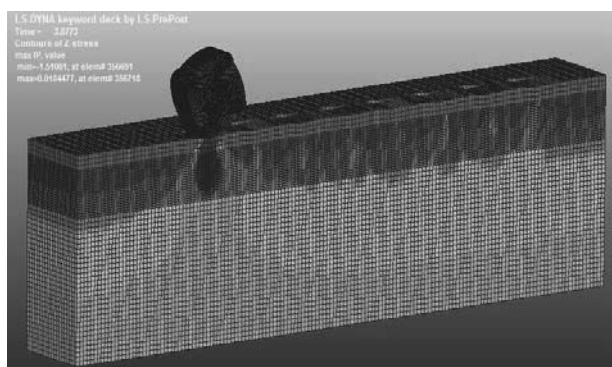


Figure 2. FEM model (Source: Fig 3, Kuo et al. 2013).

Kirstein et al. (2013) have described the application of a combination of ground improvement techniques to stabilize a recently placed brown coal landfill embankment for supporting a new road. Owing to significant stability problems and the small settlement tolerance of the structure (15 m deep), "floating" stone columns were also installed. The design and the associated settlements were significantly influenced by the combination of different soil improvement techniques. The settlement predictions were obtained using a finite element model (Figure 3) and successfully verified against the results of pressuremeter tests.

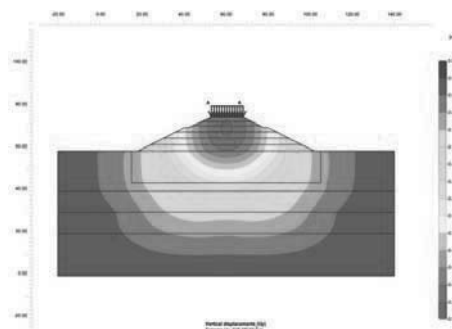


Figure 3. Representation of the predicted total settlements obtained with Plaxis (Source Fig 10, Kirstein et al. 2013).

Fonseca et al. (2013) presented some intriguing results obtained through laboratory studies performed on compacted mixtures of cement and limestone aggregates. The results indicated that the differences observed in dynamic and static stiffness properties and shear strength parameters were directly associated with the variation of porosity/cement ratio. As expected, a higher stiffness and strength were obtained by increasing the cement content and the degree of compaction. While a hardening soil model could be employed to adequately describe the observed stress-strain behaviour, the volumetric predictions and the post-peak strain softening response could not be reproduced satisfactorily.

### 3 LABORATORY TESTING

This section includes 6 articles. Two papers demonstrate the results of California Bearing Ratio (CBR) tests performed on the subbase (Ishikawa et al. 2013) and the subgrade (Moayed et al. 2013). Some studies focus on cyclic loading tests on ballast (Kumara and Hayano 2013) and subgrade (Mohanty and Chandra 2013), while the others investigate the overall performance of railway track (Calon et al. 2013, Hayano et al. 2013).

Ishikawa et al. (2013) examined the effects of freeze-thaw and water content on the deformation-strength properties of granular base materials. Two types of tests are conducted on these materials under various water contents. One test is based on the newly developed CBR equipment (Figure 4), and the other using medium-size triaxial apparatus. The freeze-thaw of granular base showed a strong influence on the fatigue life of pavement structures. When number of freeze-thaw process cycles increased, CBR values decreased regardless of the water content. Resilient modulus showed a decreasing tendency with the increasing water content.

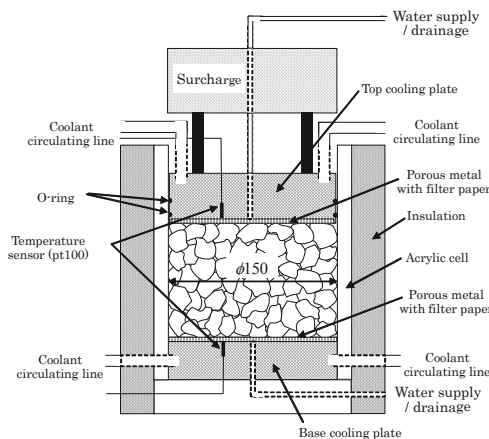


Figure 4. Freeze-thawing CBR test apparatus. (Source: Fig 1, Ishikawa et al. 2013).

Calon et al. (2013) have studied the potential benefits from the ground reinforcement by vertical soil-cement columns. Laboratory tests are performed to study the influence of the column location and the efficiency of geosynthetics on the reduction of stiff zones effects. These tests together with subsequent numerical modelling determined the optimum column layout (depth, spacing and positioning) and the effects of geosynthetics on the reduction of ballast damage.

Hayano et al. (2013) analysed the influence of ballast thickness and tie-tamper repair on the settlement of tracks by conducting a series of cyclic loading tests. Figure 5 shows the shear strain distribution generated before the tie-tamper implementation. This shear strain distribution is obtained using the method of particle image velocimetry. They found that the 250 mm ballast thickness currently adopted as the standard design is ineffective for minimizing settlement that occurs when the nonlinearity of roadbed compressibility is relatively moderate. Moreover, characteristics of the initial settlement process are altered significantly after the tie-tamper implementation, although the degree of gradual subsidence undergoes minimal change regardless of ballast thickness and roadbed type.

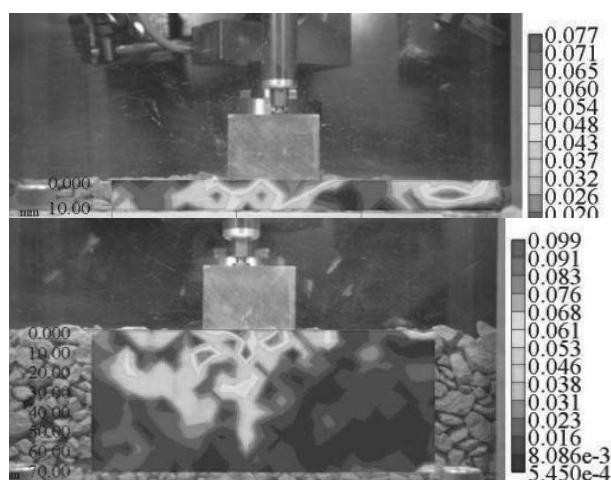


Figure 5. Distribution of maximum shear strain generated before tie-tamper implementation. (Source: Fig 5, Hayano et al. 2013).

Mohanty and Chandra (2013) have reported a series of cyclic load triaxial tests on reconstituted pond ash specimens at different moisture content and stress levels simulating environmental and traffic conditions. They concluded that both traffic and environmental conditions play an important role in the permanent axial strain behavior of the material. Furthermore, within the design context, they also highlighted the existence of a shakedown limit describing a critical stress level between stable and unstable conditions.

A series of CBR tests was conducted by Moayed et al. (2013) to investigate effects of lime-microsilica additive as a modern additive stabilizer on a silty soil to use it as a subgrade. They also evaluated the effects of the wetting-drying cycles. The CBR values were found to increase significantly as the soil was stabilized with lime-microsilica additive. An increase in the CBR values of the stabilized soil owing to wetting-drying cycles was also observed. Results showed that lime-microsilica additive can successfully be considered as a suitable option to stabilize silty soils.

Kumara and Hayano (2013) presented a series of cyclic loading models to investigate the effects of sand intrusion into ballast (i.e. fouling) and tie-tamping application on settlements of ballasted rail track. They found that the initial settlement process and the rate of residual settlement increases when the ballast is mixed with more than 30% fine materials. Therefore, tie-tamping application was found effective for fouled ballast with less than 30% fines.

#### 4 THEORETICAL ADVANCEMENTS AND CONTRIBUTIONS TO DESIGN

A total of 7 articles are categorized in the area of theoretical advancements and contributions to design. There are 6 papers investigating the behavior of road embankments (Simic 2013, Ohta et al. 2013, Shin et al. 2013, Vogt et al. 2013, Eekelen and Bezuijen 2013, Brown and Thom 2013), while one article reports the development of a non-linear ballasted track model using the finite element technique (Fernandes et al. 2013).

Brown and Thom (2013) proposed a Precision Unbound Materials Analyser (simplified version of the repeated load triaxial test) to quantify both resilient and plastic strain characteristics (Figure 6). Unlike CBR testing, this technique can be very useful in allowing the designer to evaluate alternative foundation material combinations in order to achieve the desired bearing capacity.



Figure 6. The Precision Unbound Material Analyser (PUMA) (Source: Fig 1, Brown and Thom 2013).

Simic (2013) adopted the average suction compression index of the plate loading tests and the routine soil parameters to carry out a comparison between the methods of estimating swelling. It is found that the potential vertical rise method is overly dependent on the active moisture depth, which should be adopted in the design based on the local experience.

Ohta et al. (2013) proposed the structure of seismic retrofit technique for asphalt concrete pavements using the Confined-Reinforced Earth (CRE) principle. Construction method and the results of full scale in-situ tests are well-described where the crushed stones and the associated design procedures are clearly introduced. Full-scale in-situ tests show the acceptable performance of CRE after the forced settlement to simulate severe earthquake-induced damage.

Shin et al. (2013) determined the frost penetration depth of paved road using field measurements. They found that the subbase and base courses were influenced by the temperature below 0°C regardless of the anti-frost layer. The frost penetration depth, estimated by the empirical equation proposed by Korea Institute of Construction Technology, shows a similar trend at lower frost index. This design concept is proposed for road design as an acceptable and reasonable approach.

Vogt et al. (2013) presented project-specific conditions during the dumping process, and the properties of the dumped soils along the future A-44 route. A simple model for the description of the time-dependent deformation of the dump and the effectiveness of soil compaction methods is discussed and evaluated. The simulation results and geodetic measurements reveal that by allowing a rest period of at least 6 months between the end of the dumping process and the start of the construction work, the settlements of structures and/or pavements can be reduced significantly.

Eekelen and Bezuijen (2013) compared three equilibrium models describing the phenomenon of arching in basal geosynthetically reinforced (GR) piled embankments, namely the models of Hewlett and Randolph (1988), Zaeske (2001) and the model of concentric arches by Van Eekelen (2013b). The load distributions predicted by Hewlett and Randolph (1988) and Zaeske (2001) show a uniform load distribution on the GR between the piles. The concentric arches model provides a load concentration on the GR strips, with an inverse triangular load

distribution on those GR strips. This is in agreement with the observations in scaled-down model tests, numerical analysis and field measurements.

Fernandes et al. (2013) carried out a 2D finite element model with a modified width (plane strain) where viscous boundaries are implemented using a Kelvin-Voigt viscoelastic mechanical model to reduce the wave reflexion on the boundaries. The importance of initial state evolution of track materials on the context of non-linear mechanical behaviour is discussed to assure the correct combination of laboratory tests based on the current track conditions, especially for ballast (Figure 7).

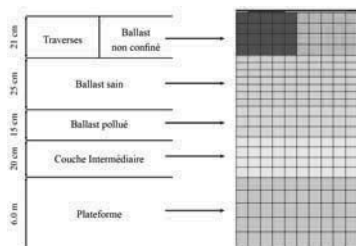


Figure 7. Finite element mesh discretisation of the railway structure (Source: Fig 3, Fernandes et al. 2013).

### 5 APPLICATIONS OF GEOSYNTHETICS

In this section, 4 articles are described. The majority of articles discuss general issues of geosynthetic reinforcement (Indraratna et al. 2013, Wayne et al. 2013, Huckert et al. 2013), while other article examines the stiffness of the soil-geosynthetic interaction under small displacement conditions (Zonberg et al. 2013).

Huckert et al. (2013) presented full-scale experiments to study load transfers of geosynthetics-reinforced embankments prone to sinkholes which are related to the complexity of various mechanisms. Numerical model coupling both finite and discrete element methods were performed and the results compared with the experimental data. These simulations provide a better understanding of load transfers towards the edges of the cavity.

Wayne et al. (2013) presented results of two field studies and model tests to evaluate performance of a geogrid-stabilized unpaved aggregate base overlaying relatively weak and non-uniform subgrade soils. Piezoelectric earth pressure cells (EPC) were used to measure horizontal stress below and above the geogrid location versus the passage of construction and truck traffic. The variation of dynamic horizontal stresses within the subgrade against the passage of truck traffic is presented in Figure 8. This result indicated an enhanced fully confined zone above the geogrid, resulting in an uniform vertical stress across the subgrade that leads to reduced lateral stresses.

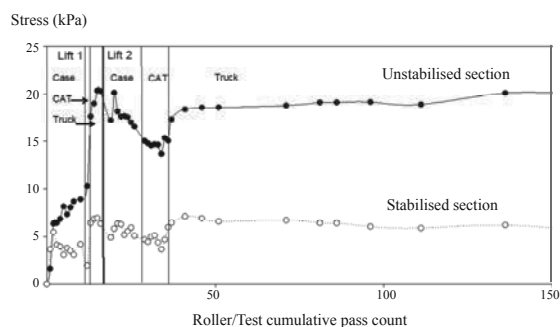


Figure 8. Horizontal stress within the subgrade layer after roller compaction and test vehicle passes (Source: Fig 3, Wayne et al. 2013).

Figure 9 presents the horizontal stress in the base layer after roller compaction and trafficking. It is clearly seen that the geogrid confines the unbound aggregate leading to an increased

lateral stress within the aggregate. The results demonstrate that the inclusion of geogrid at the interface of soft subgrade and aggregate layers affects the development of the “locked-in” horizontal stress upon loading. A higher horizontal stress within the stabilized aggregate layer gives a direct indication of the lateral restraint mechanism. The result of increased aggregate stresses leads to an increase in the resilient modulus of aggregate adjacent to the geogrid.

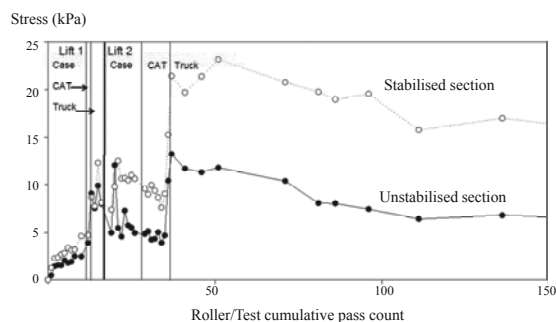


Figure 9. Horizontal stress within the base layer after roller compaction and test vehicle passes (Source: Fig 4, Wayne et al. 2013).

Indraratna et al. (2013) presented the results of full-scale field tests conducted on rail track sections in the towns of Bulli and Singleton (NSW, Australia) to measure track deformations associated with cyclic stresses and impact loads. The vertical and horizontal stresses induced in the track bed were recorded by pressure cells. Vertical deformations of the track were measured by settlement pegs, and lateral deformations were measured by electronic displacement transducers. The settlement pegs and displacement transducers were installed at the sleeper-ballast and ballast-subballast interfaces, respectively, as shown in Figure 10.

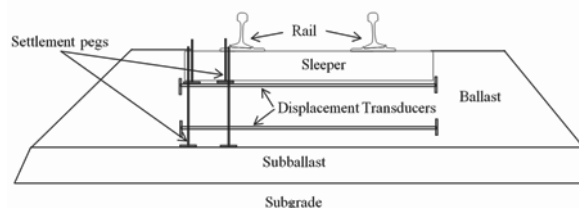


Figure 10. Installation of settlement pegs and displacement transducers at Bulli site (Source: Fig 3, Indraratna et al. 2013).

The average lateral deformations of ballast at various number of load cycles (N) are illustrated in Figure 11. It is shown that the geocomposite decreased the lateral deformation of fresh ballast by about 49% and that of recycled ballast by 11%. The capacity of the ballast to distribute loads was improved by the placement of the geocomposite, which substantially reduced settlement under high repeated loading. Indraratna et al. also discuss the results of large scale drop-weight impact testing equipment to evaluate the effect of using shock mats in mitigating ballast breakage. The ballast breakage was measured using the ballast breakage index (BBI) as shown in Table 1. Installing layers of synthetic materials such geogrids and rubber pads (shock mats) in rail tracks was found to significantly reduce ballast degradation.

Table 1. Ballast breakage under impact loading (Source: Table 1, Indraratna et al. 2013)

Base	Test Details	BBI
Stiff	Without shock mat	0.170
Stiff	Shock mat at top and bottom	0.091
Weak	Without shock mat	0.080
Weak	Shock mat at top and bottom	0.028

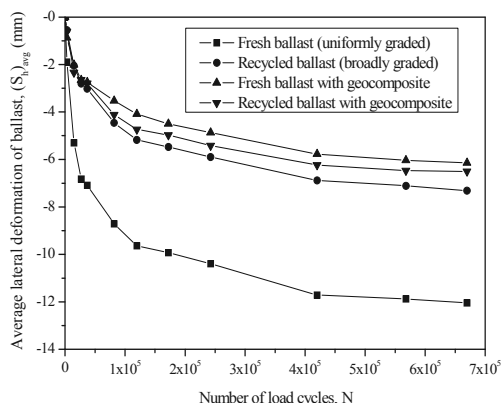


Figure 11. In-situ response of the ballast layer: lateral deformations (Source: Fig 4, Indraratna et al. 2013).

Zornberg et al. (2013) introduced a mathematical model to investigate the soil-geosynthetic interaction behavior under small displacements. A new parameter, defined as ‘Stiffness of Soil-Geosynthetic Interaction’ ( $K_{SGI}$ ) is proposed to evaluate soil-geosynthetic interaction. This parameter is capable of quantifying the performance of geosynthetic reinforcement under small displacement conditions.  $K_{SGI}$  was proposed on the assumption of a linear relationship between unit tension and strain in geosynthetic reinforcement and uniform soil-geosynthetic interface shear over the active length of the geosynthetic. Zornberg et al. (2013) conducted several geosynthetic pullout tests of biaxial geosynthetic with dimensions of  $300 \times 600$  mm in clean poorly graded sand to validate the proposed model. Figure 12 shows a good agreement between the experimental data and the results obtained with the proposed model.

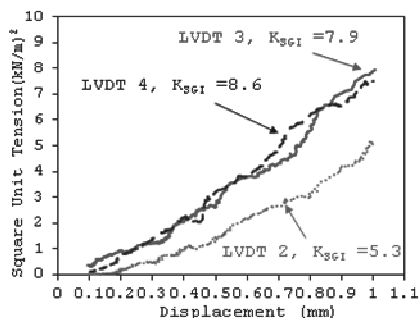


Figure 12. Results for the pullout test for LVDTs 2, 3, and 4 in ( $T^2-u$ ) space (Source: Fig 7, Zornberg et al. 2013).

## 6 NUMERICAL MODELLING

### 1.1 Finite element modelling (FEM)

There are 5 articles described in this section. The majority of the papers discuss Finite Element Modelling (FEM) on the stability analysis of soft clay subgrade and embankments (Carvajal and Romana 2013, Mansikkamaki and Lansivaara 2013, Islam et al. 2013 and Chirica et al. 2013), while one paper examines the application of a stochastic subsoil model on the deformation of bridge piers considering the soil heterogeneity (Jacobse et al. 2013).

Carvajal and Romana (2013) developed a FEM model of a multilayered system to investigate the influence of soft soil depth on pavement response during static and cyclic loading (Figure 13). They concluded that deep ground treatments should be applied to achieve an allowable capacity of soft soils up to a depth of 6 m to reduce the maintenance costs.

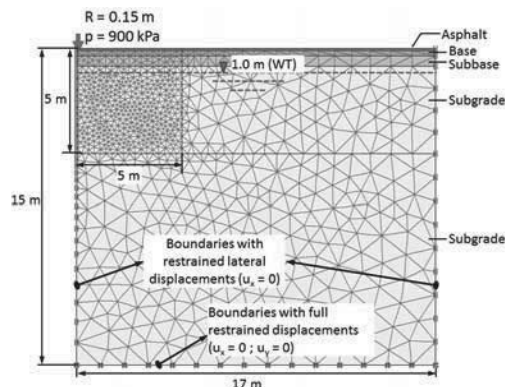


Figure 13. Geometry of the finite element model (Source: Fig.1c, Carvajal and Romana 2013).

Islam et al. (2013) investigated the long-term performance of the instrumented preloaded Nerang-Broadbeach Roadway (NBR) embankment founded on a soft sensitive estuarine clay. Fully coupled nonlinear Finite Element Analyses (FEA) were carried out adopting an elasto-viscoplastic (EVP) and an elasto-plastic Modified Cam Clay (MCC) constitutive model. It was concluded that the MCC model under-predicted the ultimate settlement whereas the creep-based EVP model captured settlement quite well, albeit over-predicting the pore pressure response (Figure 14).

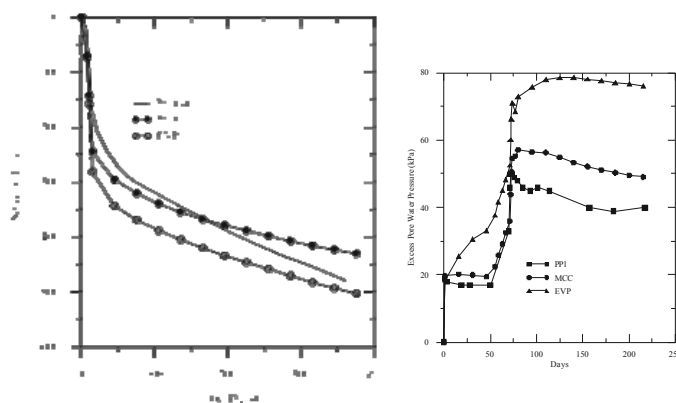


Figure 14. Comparison of measured and predicted settlements and pore water pressures (Source: Figs. 4 and 5, Islam et al. 2013).

Mansikkamaki and Lansivaara (2013) introduced a 2D and 3D FEM analysis to evaluate the embankment stability of slopes reinforced with a wooden pile structure and a sheet pile wall. Wooden piles and sheet pile walls can be used to improve embankment stability if the supporting forces are reasonable. FEM can provide valuable additional information to evaluate how sensitive the structural forces can be for the soil strength variation and also to determine what would be the real nature of the failure. Figure 15 shows the failure surfaces observed with and without reinforcement.

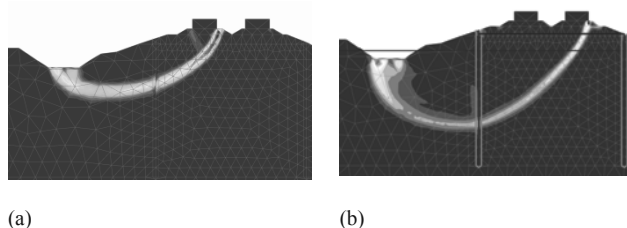


Figure 15. Failure surfaces from the safety analysis. (a) without the reinforcement (b) with the sheet pile wall (Source: Fig 8, Mansikkamaki and Lansivaara 2013).

Chirica et al. (2013) presented the analysis of a road embankment with variable height located at Iassy (Romania). The FEM model had taken into account various hypotheses: (1) modeling the soil in natural state, (2) modeling the foundation in flooded state, and (3) modelling the foundation soil in a flooded state and with different imposed consolidation conditions. They reported that out of all the test hypotheses, the flooded state exhibited the highest strain and lowest bearing capacity.

Jacobse et al. (2013) developed a 3D FEM model to capture the deformation of new lifting bridge constructed across the river Oude Maas in the Rotterdam Harbour. They applied a simplified stochastic subsoil model to quantify the risk in order to deal with the uncertainty. They highlighted that the distribution of expected rotation is more or less equal to zero (Figure 16) and was in agreement with the deterministic settlement calculations.

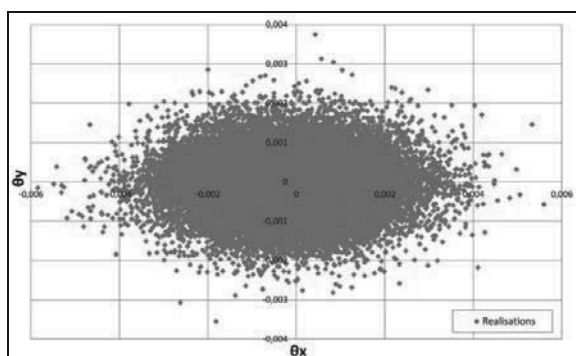


Figure 16. Results Monte Carlo analysis pier 40, residual rotations (source: Fig 4, Jacobse et al. 2013).

## 1.2 Discrete element modelling (DEM)

The use of Distinct Element Method (DEM) in transport geotechnics is gaining popularity, but regrettably there is no significant contribution made in this theme at this Conference. Therefore, for completeness of this General Report, a succinct description is provided herewith. Ballast layer is often subjected to large dynamic stresses (Yang et al. 2009), which contribute to track settlement caused by particle breakage and densification, leading to frequent maintenance (e.g. McDowell and Harireche 2002, Lobo-Guerrero and Vallejo 2006, Indraratna et al. 2010, Indraratna et al. 2012).

McDowell and Harireche (2002), and Indraratna et al. (2010) considered each particle as an agglomerate of several bonded particles. Disintegration of this agglomerate during loading is considered as breakage (Figure 17). Lobo-Guerrero and Vallejo (2006) simulated particle breakage by replacing the original particles with an equivalent set of smaller particles, when the original particle satisfies a predefined failure criterion.

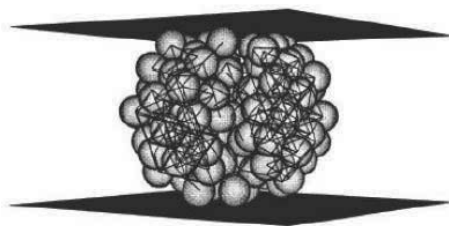


Figure 17. Final fracture of a typical 0.5 mm diameter agglomerate showing intact contact bonds (after McDowell and Harireche 2002).

Indraratna et al. (2010) developed a DEM (PFC<sup>2D</sup>) model to capture the influence of frequency on the deformation and degradation of ballast during cyclic loading. DEM simulations were performed at frequencies of 10 Hz, 20 Hz, 30 Hz, and 40 Hz and for low values of loading cycles ( $N < 1000$ ). The

cumulative bond breakage ( $B_r$ ), defined as a percentage of bonds broken compared to the total number of bonds is shown at different  $f$  and  $N$  (Fig. 18). It is observed that  $B_r$  increases with the increase in  $f$  and  $N$ . Most of the bond breakages occurred during the initial cycles of loading, causing rapid permanent deformation at the start of loading, as this is exactly what is observed on new tracks upon the passage of initial trains.

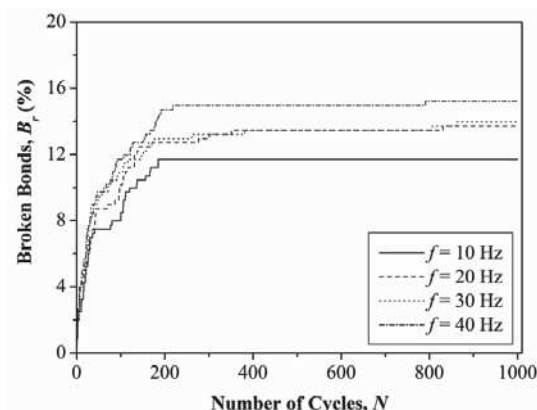


Figure 18. Effects of frequency ( $f$ ) on bond breakage ( $B_r$ ) with number of cycles ( $N$ ) (after Indraratna et al. 2010).

Huang and Tutumluer (2011) assessed the behavior of fouled ballast using a “half-track” 2D DEM model. They studied the effects of different percentages of fouling and the corresponding and locations on track settlement. Recently, Indraratna et al. (2012) employed a 3D DEM model to study the shear behaviour of fresh and coal fouled ballast in direct shear testing. Fouled ballast with void contaminant index (VCI) ranging from 20% to 70% was modeled by injecting a specified number of miniature spherical particles into the ballast voids. The micro-mechanical observations obtained through DEM studies imply that fouling decreases particle breakage due to diminished stress concentrations or contact forces between ballast grains, but considerably impedes drainage when the VCI > 40%.

## 2 FIELD PERFORMANCE EVALUATION

There are 6 papers that have been included in this section. Two papers discuss the results of monitoring of full scale embankments used for ground improvement (Boutonnier et al. 2013, Buggy 2013) while one paper focuses upon the stability and settlement analysis of the road embankment (Murjanto et al. 2013). Effects of moisture, mechanical indices and asphalt reinforcement on the performance of concrete pavements are presented (Teltayev 2013, Touole and Thesseling 2013). Laboratory studies as well as field studies are conducted to evaluate the performance of shale as fill and embankment material (Solomon et al. 2013).

Boutonnier et al. (2013) describe the monitoring of six full-scale embankments to measure settlements and the time of consolidation. They estimate the preconsolidation pressure using undrained cohesion  $C_u$  and consider the coefficient of consolidation  $C_v$  as ten times the laboratory measured  $C_v$  value. They further conclude that the calculated settlements and time of consolidation are in good agreement with the measurements. Buggy (2013) describes the observational approach used to control embankment stability primarily by means of monitoring filling rates, pore pressures and deformation ratio (ratio of lateral toe displacement to vertical crest settlement). Embankments up to 10 m height are constructed in multiple stages with continuous monitoring of performance by means of piezometers, inclinometers, settlement plates and survey monuments. A combination of prefabricated vertical drain

(PVD), geosynthetic basal reinforcement and 2 to 2.5 m of surcharge is adopted for ground improvement. A typical filling rate and deformation ratio history for one of the instrumented locations is shown in Figure 19. Buggy (2013) concludes that deformation ratios offer a reliable method for controlling stability of multi-stage embankments when used in conjunction with pore pressure instrumentation.

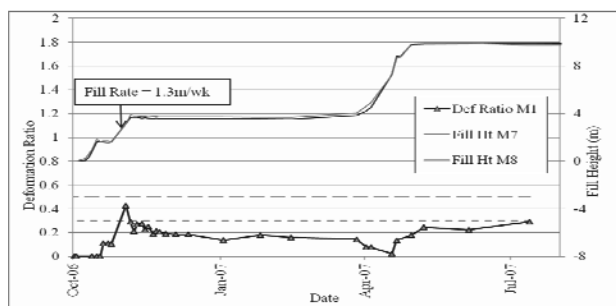


Figure 19. A typical filling rate and deformation ratio history for the instrumented location at Ch 4+185 m (Source: Fig 2, Buggy 2013).

Murjanto et al. (2013) presented a comprehensive stability and settlement analysis of the road embankment using a detailed site investigation. A 7.3 km long embankment with flexible pavements is built over North Jakarta-soft alluvial deposit. The pavement level was raised several times in order to compensate for the settlement. The results of the stability analysis indicated that the road is relatively in critical condition and some proposed trial designs were analyzed to fulfill minimum FS by strengthening of the road embankment using: (i) corrugated prestressed concrete sheet piles; (ii) corrugated prestressed concrete sheet piles and horizontal bars; (iii) concrete sheet piles and ground anchor; and (iv) secant pile walls.

The variation of moisture and mechanical indices on the soil basement is often neglected while designing concrete pavements. An interesting study addressing these issues is reported by Teltayev (2013). He has shown that the sagging, tensile stress and vertical deformation of the surface of soil basement are very sensitive to seasonal climate changes. He has mentioned that design of cement concrete slabs often incorporate sagging of pavement in spring, however sagging also increases in summer and autumn seasons and this can be the cause of various forms of cracks (Figure 20).

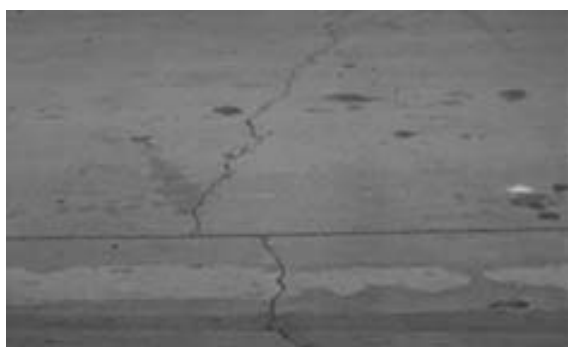


Figure 20. Transversal crack in cement concrete pavement (Source: Fig. 8, Teltayev 2013).

In another study by Toule and Thesseling (2013), tensile strengths of two different asphalt reinforcement products with different raw materials (polyester and fiberglass) are analysed considering the influence of installation damage. Results of full-scale tests after loading from truck passes and asphalt compaction revealed that the polyester grid undergo a loss of 30% of its tensile strength while the fiberglass grid showed a loss of strength up to about 90%. The fiberglass grid was damaged significantly more than the polyester grid reinforcement (Figure 21).

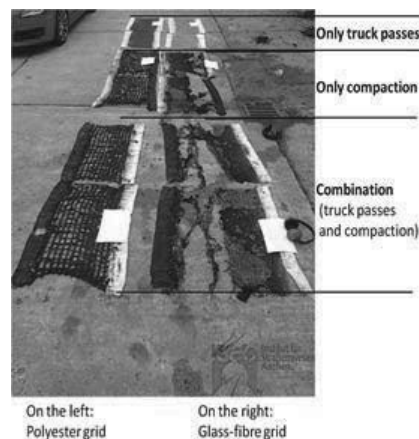


Figure 21. Results of installation damage test (Source: Fig 5, Toule and Thesseling 2013).

Solomon et al. (2013) described the performance of shale as fill and embankment material through laboratory studies and field trials. In order to reduce costs involved in the hauling of suitable material over longer distances, possible use of shale is evaluated. Laboratory tests including index properties, compaction, California Bearing Ratio (CBR) and triaxial tests are conducted at six different laboratories and the results, particularly the CBR values indicated that the shale was of marginal quality for its intended purposes. However, in a field trial road section constructed using the shale that was monitored for a period of two months, the results indicated high CBR and bearing resistance values with insignificant settlement. The field performance based characteristics of the shale merited its selection for use.

### 3 CONCLUSIONS

The Discussion Session TC202 on Transportation of the 18th ICSMGE consists of 33 papers (135 pages) describing numerous efforts on experimental research, field monitoring and data interpretation, design approaches, analytical methods and numerical modelling in six distinct categories:

- Compaction and subgrade improvement
- Laboratory testing
- Theoretical advancements and contributions to design
- Applications of geosynthetics
- Numerical modelling
- Field performance evaluation

In this General Report, an attempt has been made to offer a critical review of the majority of papers that have made a significant contribution in the area of Transportation, and the salient aspects of all papers have been summarised in the Annexure (Tables 2-7). Considering the extensive worldwide efforts put in by practitioners, academics, research associates and research students (125 contributors from 19 countries), there is no doubt that this Technical Session has offered one of the most comprehensive compilations in Transport Geotechnics, representing its current state-of-the-art. However, it is noted that only a limited number of evolving techniques have been presented to any significant extent, and these include load transfer analyses including probabilistic approaches, seismic retrofitting, intelligent compaction control, micro-mechanics of granular media through DEM modeling, analysis of soil-geosynthetic interfaces, stabilization of rail and road sub-base and sub-ballast using geocells, and other ground improvement methods addressing problematic subgrade, among others. While some additional papers are cited in this General Report especially in DEM modeling of granular media, further details of evolving techniques in Transport Geotechnics have been



reported by Correia et al. (2012), Correia et al. (2007) and Indraratna et al. (2011).

#### 4 ACKNOWLEDGEMENT

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(Please see Tables 2-7)

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## 6 ANNEXURE - TABLE 2-7: SUMMARY OF ALL CONTRIBUTIONS IN DISCUSSION SESSION

Table 2. Compaction and subgrade improvement for transport infrastructure

Title of Paper	Authors	Country	Summary of Main Contribution
Five years of Impact Compaction in Europe – successful implementation of an innovative compaction technique based on fundamental research and field experiments	Adam D., Paulmichl I., Adam C. and Falkner F.J.	Austria	<p>The impact compaction methods are more efficient if greater depths of densification are of interest.</p> <p>Key aspects related to the application of impact compaction such as the surface velocity, weight and number passes are analyzed both in numerical simulations and field cases studies. The results are compared and compaction efficiency is also linked to the type of soil.</p>
Assessing the Effectiveness of Rolling Dynamic Compaction	Kuo Y.L., Jaksa M.B., Scott B.T., Bradley A.C., Power C.N., Crisp A.C. and Jiang J.H.	Australia	<p>The efficiency of rolling dynamic compaction (RDC) is examined by means of a combination of field studies and numerical modeling</p> <p>RDC is more effective for depths between 0.8 m to 3.0 m and the most significant factors governing its efficiency are soil cohesion, Poisson's ratio and shear modulus, as well as the width and mass of the RDC module.</p>
Applicability of the Geogauge, P-FWD and DCP for compaction control	Conde M. C., Lopes M. G., Caldeira L. and Bilé Serra J.	Portugal	<p>The feasibility of a stiffness-based specification for embankment soil compaction quality control is discussed.</p> <p>DCP equipment showed greater suitability as a compaction control tool, due to the strong negative correlation with water content values.</p>
Ground improvement methods for the construction of the federal road B 176 on a new elevated dump in the brown coal region of MIBRAG	Kirstein J. F., Ahner C., Uhlemann S., Uhlich P. and Röder K.	Germany	<p>The design and the settlements are significantly optimized by the combination of different soil improvement techniques, particularly in cases where significant stability problems are expected.</p> <p>The settlements predictions by Finite element modeling agreed well the results obtained with in situ pressuremeter tests.</p>
Laboratory characterization and model calibration of a cemented aggregate for application in transportation infrastructures	Viana da Fonseca A., Rios S., Domingues A.M., Silva A. and Fortunato E.	Portugal	<p>The differences observed in dynamic and static stiffness properties and shear strength parameters of compacted mixtures of cement and limestone aggregate are directly associated to the variation of porosity/cement ratio.</p> <p>Hardening soil models may be employed to describe the stress-strain behavior, but do not provide satisfactory predictions of the volumetric behavior and post-peak strain softening.</p>

Table 3. Laboratory Testing

Title of Paper	Authors	Country	Summary of Main Contribution
Railways platforms reinforced by soil-mixing columns without track removing	Calon N., Robinet A., Costa S., D'Aguiar L., Cojean, B.C. and Mosser J.F.	France	<p>Investigated the potential benefits from the ground reinforcement by vertical soil-cement columns</p> <p>Performed laboratory tests to investigate the influence of the column location and the efficiency of geosynthetics on the reduction of stiff zones</p> <p>With subsequent numerical model, they determined the optimum columns mesh</p>
Effects of ballast thickness and tie-tamper repair on settlement characteristics of railway ballasted tracks	Hayano K., Ishii K. and Muramoto K.	Japan	<p>Conducted a series of cyclic loading tests on model grounds to investigate the effects of ballast thickness and tie-tamper repair on the settlement characteristics of ballasted tracks</p> <p>Maximum shear strain distributions generated in the model grounds were analyzed with particle image velocimetry</p>
Effect Evaluation of Freeze-Thaw on Deformation-Strength Properties of Granular Base Course Material in Pavement	Ishikawa T., Zhang Y., Kawabata S., Kameyama S., Tokoro T. and Ono T.	Japan	<p>CBR tests of freeze-thawed subbase course materials under various water contents, and the resilient modulus tests in unsaturated condition were conducted using two newly developed test apparatus</p> <p>The test results were compared with long-term field measurement at a model pavement structure, including FWD tests</p>
On the Permanent Deformation Behavior of Rail Road Pond Ash Subgrade	Mohanty B. and Chandra S.	India	<p>Repeated load triaxial tests were conducted on reconstituted pond ash specimens</p> <p>Permanent deformation calculations take into account the stress history</p>

			and number of passes of vehicular traffic loading. Test results were analyzed to study the effects of confining pressure, deviatoric stresses, and degree of saturation on the permanent deformation response of pond ash.
Effect of wetting- drying cycles on CBR values of silty subgrade soil of Karaj railway	Moayed R.Z., Lahiji B. P. and Daghigh Y.	Iran	Conducted series of CBR tests to investigate the effect of lime-microsilica additive as a modern additive stabilizer on a silty soil. Lime and microsilica were mixed with the soil in different percentages and specimens were prepared at optimum moisture content.
Model tests on settlement behaviour of ballasts subjected to sand intrusion and tie tamping application	Kumara J. and Hayano K.	Japan	Model tests were conducted on 1/5th scale of the actual size of railway track. The relationship between the number of loading cycles and settlement was obtained and results were discussed with degree of ballast fouling.

Table 4. Theoretical Advancements and Contributions to Design

Title of Paper	Authors	Country	Summary of Main Contribution
Evaluation of roadbed potential damage induced by swelling/shrinkage of the subgrade	Simic D.	Spain	The average suction compression index of the plate load tests and the routine soil parameters were adopted to carry out a comparison between the methods of estimating swelling deformation. The potential vertical rise method is very dependent on the active moisture depth, which should be adopted based on the local experience.
Development of a non-linear ballasted railway track model	Fernandes V.A., D'Aguiar S. C., and Lopez-Caballero F.	France	A 2D finite element model with a modified width plane strain condition is used where viscous boundaries are implemented using a Kelvin-Voigt viscoelastic mechanical model to reduce wave reflexion on boundaries. The importance of initial state evolution of track materials on the context of non-linear mechanical behavior is discussed to assure the correct combination of laboratory tests based on current track conditions, especially ballast.
Seismic Retrofit Technique for Asphalt Concrete Pavements	Ohta H., Ishigaki T. and Tatta N.	Japan	The structure of the seismic retrofit technique for asphalt concrete pavements using Confined-Reinforced Earth (CRE), construction method and the results of full scale in-situ tests were described where crushed stones and new design procedures were introduced. Full scale in-situ tests show the acceptable performance of CRE after the forced settlement to simulate the severe earthquake-induced damage.
Influence of Anti-freezing on the Frost Penetration Depth for Paved Road Design	Shin E.C., Cho G.T. and Lee J.S.	Korea	The frost penetration depth of paved road was determined by the field measurement. The subbase and base courses are influenced by the temperature below 0o regardless of anti-frost layer. The frost penetration depth estimated by the empirical equation proposed by Korea Institute of Construction Technology shows a similar trend in lower frost index. The reasonable design concept is proposed for road design.
Special Aspects for Building a Motorway on a 185 m Deep Dump	Vogt N., Heyer D., Birle E., Vogt S., Dahmen D., Karcher C., Vinzelberg G. and Eidam F.	Germany	The paper presents the project-specific conditions during the dumping process and the properties of the dumped soils along the future A 44 routing. A simple model for the description of the time-dependent deformation of the dump and the effectiveness of soil compaction methods is discussed and evaluated. The simulation results and geodetic measurements have shown that by allowing the resting period of at least 6 months between the end of the dumping process and the start of the construction work, the settlements of structures or pavements can be reduced significantly.
Equilibrium models for arching in basal reinforced piled embankments	Eekelen S.J.M. and Bezuijen A.	Netherlands	The paper compares three equilibrium models describing arching in geosynthetic basal reinforced (GR) piled embankments, namely the models of Hewlett and Randolph (1988), Zaeske (2001) and the concentric arches model of Van Eekelen (2013b). The load distributions predicted by Hewlett and Randolph (1988) and Zaeske (2001) show a uniform load distribution on the GR between the piles. The concentric arches model (Van Eekelen et al. 2013b) provides

			a load concentration on the GR strips with an inverse triangular load distribution on those GR strips. This is in agreement with observations in scaled model tests, numerical analysis and field measurements.
Recent developments in pavement foundation design	Brown S.F. and Thom N.H.	United Kingdom	<p>A Precision Unbound Materials Analyzer (simplified version of the repeated load triaxial test) has been developed to quantify both resilient and plastic strain characteristics.</p> <p>Unlike CBR testing, this technique can be very useful in allowing a designer to evaluate alternative foundation material combinations in order to achieve a desired foundation.</p>

Table 5. Applications of Geosynthetics

Title of Paper	Authors	Country	Summary of Main Contribution
Load transfer mechanisms in geotextile-reinforced embankments overlying voids: experimental and numerical approaches	Huckert A., Garcin P., Villard P., Briançon L. and Auray G.	France	<p>Full-scale experiments were conducted on non-cohesive granular embankments to study load transfers of geosynthetics-reinforced embankments prone to sinkholes.</p> <p>Numerical model was performed to provide a better understanding of the load transfers towards the edges of the cavity</p>
Performance verification of a geogrid mechanically stabilised layer	Wayne M., Fraser I., Reall B. and Kwon J.	USA	<p>Series of full-scale field tests and model tests were conducted to evaluate performance of a geogrid- stabilized unpaved aggregate base overlaying relatively weak and non-uniform subgrade soils.</p> <p>The results confirm that the geogrid promotes improved aggregate confinement and interaction, leading to enhanced structural performance of the unpaved aggregate base.</p>
Performance Assessment of Synthetic Shock Mats and Grids in the Improvement of Ballasted Tracks	Indraratna B., Nimbalkar S., Rujikiatkamjorn C., Neville T. and Christie D.	Australia	<p>Full-scale field tests were conducted on rail track sections in the towns of Bulli and Singleton (Australia) to measure track deformations associated with cyclic stresses and impact loads.</p> <p>The results indicated that the use of geocomposites as reinforcing elements for ballast proved to be a feasible and economically attractive alternative.</p>
Characterization of Soil-Geosynthetic Interaction under Small Displacements Conditions	Zornberg J.G., Roodi G.H., Gupta R. and Ferreira J.	USA	<p>A mathematical model with a new parameter, defined as “Stiffness of Soil-Geosynthetic Interaction” or <math>K_{SGI}</math>, was introduced to address soil-geosynthetic interaction behavior under small displacements.</p> <p>Pull out tests with geosynthetics embedded in poorly graded sand were conducted to evaluate the proposed model.</p>

Table 6. Numerical Modeling

Title of Paper	Authors	Country	Summary of Main Contribution
Analysis of the influence of soft soil depth on the subgrade capacity for flexible pavements.	Carvajal E. and Romana M.	Spain	<p>Presented the analyses of a flexible pavement structure founded on soft soil subgrade, through the FEM of a multilayered system.</p> <p>Deep ground treatments should be applied to achieve an allowable capacity of soft soils up to minimum depth of about 6 m, otherwise maintenance cost of pavements might be excessive.</p>
Long-term performance of preloaded road embankment	Islam M.N., Gnanendran C.T., Sivakumar S.T., Karim M.R.	Australia	<p>Investigated the long-term performance of the preloaded Nerang-Broadbeach Roadway (NBR) embankment near the Gold Coast in Queensland (Australia).</p> <p>The MCC model under-predicted the ultimate settlement while the creep-based EVP model captured it well but over-predicted the pore pressure response.</p> <p>The modified calculation of the Asaoka method predicted almost identical magnitudes of ultimate settlement as the Hyperbolic method and FEAs.</p>
Stability improvement methods for soft clays in a railway environment	Mansikkamäki J. and Lämsivaara T.	Finland	<p>This paper introduces an evaluation of alternative methods to improve embankment stability with wooden pile structures or with sheet pile walls.</p> <p>Based on the 2D and 3D finite element analysis and to the soil behavior calibrated in the failure test and existing, they highlighted that analysed railway embankments are under poor stability conditions.</p>
Probabilistic Settlement Analysis For The Botlek Lifting Bridge	Jacobse J.A., Nehal R.S., Rijneveld B.	Netherlands	Presented the deformation analysis, deterministic 3D FEM calculations, on a lifting bridge constructed across the river Oude Maas in the

Design	and Bouwmeester D.	Rotterdam harbour area	Application of a simplified stochastic subsoil model captured quantitative risk analysis in order to deal with the uncertainties.
The geotechnical analysis corresponding to the high road embankments close to a bridge	Dragos A.C., Tenea V. D.	Romania	Presented a complex case study corresponding to a road embankments upto 10m height placed at Iassy (Romania).  The analysis shows high strain and low bearing capacity for soils in flooded state.

Table 7. Field Performance Evaluation

Title of Paper	Authors	Country	Summary of Main Contribution
LGV EST section 41 : measured and calculated settlements under embankments	Boutonnier L., Hajouai F., Bacar Fadhuli N. and Gandille D.	France	Six embankments are monitored to measure the settlements and the time of consolidation.  The preconsolidation pressure of the soil is estimated from the undrained cohesion $C_u$ and the coefficient of consolidation $C_v$ used in the design was ten times the $C_v$ measured with laboratory test.
Influence of installation damage on the tensile strength of asphalt reinforcement products	Touole L.S. and Thesseling B.	Germany	The effective tensile strength of asphalt reinforcement products, considering installation damage was analysed.  A considerable difference in loss of tensile strength, due to the effects of installation damage was observed.
Influence of Mechanical Indices for Soil Basement on Strength of Road Structure	Teltayev B.	Kazakhstan	Moisture value and its phase content in soil basement of the highway vary substantially in annual cycle and according to the depth of basement.  The maximum values of sagging, tensile stress and vertical deformation of cement concrete pavement occur in summer and autumn seasons.
The performance of shale as fill and embankment material for a trunk road in Ghana	Solomon K.M., Oddei J.K. and Gawu S.K.	Ghana	The CBR values indicated variations between 8% and 12%, which are below the contract special specification minimum value of 15%. This was therefore considered as having marginal quality for its intended purposes.  Results obtained from the field evaluation indicated high CBR and bearing resistance values including insignificant settlement.
Evaluation of the Performance of Road Embankments over North Jakarta-Soft Soils	Murjanto D., Rahadian H., Hendarto and Taufik R.	Indonesia	To fulfill stability and settlement analysis, the road at Zone 1, and 3 should be strengthened by secant pile walls combined with raising of 0.7 m.  The road at Zone 2 should be strengthened by concrete sheet piles and ground anchor.
Deformation Performance and Stability Control of Multi-stage Embankments in Ireland	Buggy F.J.	Ireland	Deformation ratios offer a reliable method for controlling stability of multi-stage embankments when used in conjunction with pore pressure instrumentation. For the specific conditions at Limerick Tunnel, a limit deformation ratio of 0.6 was shown to give satisfactory performance and acceptable stability.  Excessive lateral deformation related to local failure occurred at several locations in the vicinity of creeks, ditches and historical excavations located within 10 m of the embankment toe.