Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-3021

Technical session 2b: Reinforcement and stone columns

Séances techniques 2b: Renforcement et colonne de pierre

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1 INTRODUCTION

This technical session report summarizes the papers collected under the themes of soil reinforcement and stone columns.

As a starting point to organize the papers in this session and guide discussion on aspects of the contents of each paper, two tables are presented. Table 1 shows papers identified by author names that have been grouped under the reinforcement theme. Table 2 refers to papers that are focused on stone columns. The two themes represent different technologies and are not normally linked. Interestingly, there is one paper that does describe one project in which both stone columns and geosynthetic basal reinforcement of a railway embankment were employed synergistically (Heitz et al.).

2 REINFORCEMENT

2.1 *General*

Table 1 shows that a total of 20 papers with the common theme of reinforcement were submitted by authors from 13 different countries. The reinforcement applications that are addressed include: retaining walls, bridge abutments, slopes, embankments, dikes and shallow foundations. The largest number of papers falls within the wall category. The reinforcement materials considered are largely sheet geosynthetics (geogrids and geotextiles), but papers describing the use of passive piles for slope reinforcement, fibre-reinforced soil and soil nails also appear in this session. The papers can be further categorized by investigation type. For example, many of the papers used numerical modelling as part of the study or laboratory testing. In most cases, these papers involved parametric analyses to investigate the influence of different property values on the behaviour of numerical models, laboratory test specimens or laboratory models. A number of field experiments and case studies are also presented.

2.2 *Geosynthetic-reinforced soil walls*

Almost half of the papers in the reinforcement portion of this session deal with retaining wall structures. Papers that involve retaining walls reinforced with horizontal layers of geosynthetic or wire mesh reinforcement are described here.

The paper by Aoki et al. describes a hybrid technology in which horizontal layers of geosynthetic reinforcement are used in conjunction with a cement-stabilized backfill. The use of a cement-stabilized backfill has many advantages: settlements associated with abutment approach fills for roads and railways are reduced, and earth forces are reduced. The seismic resistance of the bridge abutments constructed with a cement-stabilized backfill is further enhanced with the inclusion of geosynthetic reinforcement. An instrumented prototype field case is used to demonstrate the construction steps used to build these hybrid structures. The same structure was test loaded to measure load-displacement response under simulated seismic loading. A simple model for the seismic design of the bridge abutment is included in the paper using non-linear springs to represent the reinforcement at the contact with the concrete facing and between the abutment base and foundation. The paper is an excellent example of a full-scale test program that clearly demonstrates proof of concept.

The paper by Benjamim et al. is an excellent example of a comprehensive research program that combines full-scale monitored reinforced soil wall structures with numerical modelling. The larger research program of eight different structures mentioned in the paper will help to fill a gap in the literature regarding the monitored performance of geotextile-reinforced retaining walls. The authors present preliminary FEM results used to reproduce the performance of one structure (reinforcement strains and facing displacements). Where there are differences between computed and measured results, the authors give explanations. Their results give confidence that properly posed numerical models verified against measured reinforcement strains and facing displacements can be used to extend the database of monitored structures at much less expense.

Freitag et al. present a construction strategy that involves precasting short reinforcement lengths into the back of concrete facing panels for facing stability. Overlapping longer primary reinforcement layers are placed in the reinforced soil zone to stabilize the backfill, but are not connected to the facing. The authors conclude that this technique may assist to reduce connection forces which are often the highest reinforcement loads in reinforced soil walls constructed with a hard facing. Their hypothesis is demonstrated through the use of a FLAC model.

Saramago and Ehrlich present a paper to demonstrate (using instrumented full-scale physical models) the influence of soil compaction on lateral earth pressures, wall deflections and reinforcement tension in soil-reinforced modular block walls. This paper addresses an important issue that has been largely ignored in current design practice for modular block walls.

The one exception to the use of geosynthetic reinforcement for retaining wall construction is the paper by Stanic et al. Their paper is a parametric study of wire mesh gabion-faced walls with a crushed rock backfill. The parametric study was carried out using a non-linear FLAC model. The wire mesh and rock fill properties were taken from independent laboratory testing. Comparison with field performance is not presented that could be used to evaluate the accuracy of the numerical predictions. However, the parametric analysis examining the influence of wall geometry and component material properties on wall deflections and reinforcement loads is large.

Table 1 Summary of reinforcement papers

Authors	Country	Application							Reinforcement type				Investigation type							Other comments
		Walls	Bridges abutments	Slopes	Embankments	Dikes	Shallow foundations	Other	Planar or strip	Piles	Fibre	Nails	Seismic/dynamic	Parametric	Analytical modelling	Numerical modelling	Field experimental	Case study	Laboratory	
Aoki et al.	Japan	x	x						geogrid				x			x	x	x		cement-treated backfill
Bellezza & Pasqualini	Italy			x						x				x		x				
Benjamin et al.	Brazil & USA	x							geotextile					x		FEM	x			comparison of physical and numerical results
Consoli et al.	Brazil & UK										x			x					direct shear	
Davies & Morgan	UK			x	x							x		x	x				centrifuge	
Freitag et al.	France	x							polyester strap					x		FLAC				
Gualco & Berardi	Italy						x		composite geogrid-geotextile					x					x	
Justo et al.	Spain				x	x			geotextile							FEM		x		
Kim et al.	Korea	x							steel						x			x		
Li & Zornberg	USA										x			x					direct shear	
Matsuoka et al.	Japan & China							roads	not given				x				x		x	soil bags
Moraci & Recalcati	Italy								geogrid					x					pullout	
Mulabdic et al.	Croatia								geogrid					x					pullout	wave velocity measurement
Patra et al.	India & USA						x		geogrid					x	x				x	
Saramago & Ehrlich	Brazil	x							geogrid					x					x	
Sayao et al.	Brazil			x								x						x		instrumented
Stanic et al.	Croatia	x							wire mesh					x		FLAC				gabion face walls
Steenbergen-Kajabova et al.	Netherlands	x										x				FEM & TALREN		x		
Uchimura & Mizuhashi	Japan		x					piers	geogrid & aluminium										model & triaxial	soil bags at facing
Heitz et al.	Germany				x				geogrid	x					x		x	x	x	stone columns
Count	13	7	2	3	3	1	2	2	14	2	2	3	2	12	4	7	4	7	11	

2.3 *Soil nailing*

Three papers have as a common theme the use of soil nails for ground improvement.

Sayão et al. present a comprehensive case study of a 40-m high nailed slope in Brazil used to stabilize an excavation in a residual gneissic soil. The project description includes details of the design, analysis, construction and instrumentation (strain gauged soil nails, horizontal tell-tales and slope inclinometers).

Steenbergen-Kajabová et al. present an interesting case study from the Netherlands in which soil nails were used to stabilize a medieval brick wall. Project constraints included the preservation of the ecosystem at the site and minimum disturbance to adjacent infrastructure. Construction was challenged by the need to restore the unstable brick facing by injection mortaring.

Davies and Morgan report the use of a laboratory investigation in which a centrifuge was used to investigate serviceability performance of soil nailed slopes under short-term and long-term conditions. The authors demonstrate that reductions in effective stresses that may be caused by hydrological conditions in the field may cause significant changes in nail axial loads. Their work has important implications to the design of soil slopes that may appear conservatively designed based on short-term stability analyses, but develope a lower factor of safety with time.

2.4 *Other reinforced structures*

Kim et al. describe an earth retention system that uses prestressed steel cables oriented parallel to the back of a strut and steel sheet pile wall. The cables add stiffness and strength to these systems used in braced excavations. The paper includes measurements and observations made at a field structure. The technique holds promise to reduce wall deformations compared to conventional braced excavation structures.

A case study of four embankment dikes in Spain is reported by Justo et al. The reinforcement component of the design was a geotextile layer placed at the base of the embankments. However, the stability of the structures was further improved by prefabricated vertical drains (PVDs). The paper gives details of the numerical models used to ensure the stability of the structures. The improvement in consolidation rates due to the use of PVDs is demonstrated by field monitoring.

Bellezza and Pasqualini report the results of a parametric analysis that investigates the use of rows of passive piles to stabilize slopes. They compare the results of reinforced and unreinforced slope configurations using dimensionless parameters quantifying a range of soil properties, slope geometry, pile location, mechanical properties and dimensions. The paper provides usefull recommendations regarding the optimal geometrical arrangement of the piles for the conditions assumed.

Matsuoka et al. report the results of an investigation using laboratory and field testing to investigate the use of layers of soil bags to reduce vibrations below road pavements. A case study with concrete and asphalt pavements supported by a granular base layer over a subbase of soil bags is also reported. These field installations were instrumented to show proof of concept. The geosynthetic material used to construct the soil bags is not reported.

The final paper in this category is the paper by Uchimura and Mizuhashi. Their paper is focused on the performance of small-scale model piers, internally reinforced with geogrid and metallic layers. The 600-mm high models were subjected to cyclic loading. The authors conclude that under small-amplitude cyclic loading, the stiffness of the soil infill was more important than the stiffness of the three different reinforcement materials investigated. The results of this test program have important implications to the design of reinforced piers used to support railway and road bridge abutments.

2.5 *Reinforcement and stone columns*

As noted in the introduction, the paper by Heitz et al. reports a case study in which both geosynthetic reinforcement and stone columns were used. The paper describes the initial failure of a railway embankment over soft organic soils that was supported by grouted stone columns connected by a single layer of geogrid reinforcement. Shortly after construction large settlements occurred. This paper is an excellent case study that looks at the reasons for the initial failure, the analyses used to redesign the structure (including three layers of geogrid reinforcement), and ultimately the rebuilding of the failed embankment sections. The new design was verified by instrument measurements. The authors give details of the analytical models used in the redesign. The new design method represents the state of the art for this hybrid technology.

2.6 *Laboratory testing of fibre-reinforced soil*

Two papers focused on fibre-reinforced soils appear in this session. Both involve laboratory testing to gather mechanical properties.

Li and Zornberg used a modified direct shear box to perform pullout tests on individual fibres. The tests were used to deduce the interface friction strength between the fibres and the soil matrix. The data provides input for analysis methods that are carried out using a discrete mechanical model approach for fibre-soil composites.

Consoli et al. investigated the large shear deformation behaviour of fibre-reinforced sand using a ring shear apparatus. The experimental results show that the shear strength of fibre-sand mixes extends to shear strains well beyond the 20% strain level that has been demonstrated in previous studies that used triaxial or conventional direct shear test equipment.

2.7 *Laboratory pullout testing*

Moraci and Recalcati report the results of a series of conventional pullout tests on three different geogrid products in combination with a compacted granular soil.

A novel variation on pullout testing is reported by Mulabdic et al. They report the results of a preliminary research program in which shear (S) wave and compression (P) wave velocity measurements are used to investigate local changes in soil stiffness (E and G modulus values). However, the paper reports only the results of measurements prior to specimen pullout (i.e. initial compacted condition of the geogrid-soil specimens). No difference within experimental measurement was detected for the value of E, that could be attributed to the presence of the geogrid inclusion. The authors reference an earlier work in which similar measurements showed an increase in shear modulus (G) of the soil during direct shear tests. Further experimental work is planned to investigate changes in E and G modulus values. The results of the proposed work hold promise to generate model parameters for numerical models of soil-geogrid interaction.

2.8 *Laboratory testing of shallow foundations*

Two papers report the result of model tests carried out to investigate footing behaviour over foundations reinforced with horizontal layers of geosynthetics. The papers by Gualco and Berardi, and Patra et al. add to a body of similar work in the

Table 2 Summary of papers on stone columns

Authors	Country	Application			Investigation type						Other
		Load support	Settlement	Consolidation	Parametric	Analytical modelling	Numerical modelling	Field testing	Case study	Laboratory	
Clemente et al.	USA	x	x				3D FLAC				
Fessi and Bouassida	Tunis		x	x			x				
Magnan et al.	France		x								influence of soil strength and installation on stone column performance
Maurya	India	x	x			x		x	x		
Pulko and Majes	Slovenia	x	x		x	x	x				
Shroff and Patel	India	x	x	x						x	
Tan and Oo	Singapore			x			FEM		x		
Dittrich et al.	Canada & Barbados	x	x				FEM	x	x		
Count	8	5	7	3	1	2	5	2	3	1	

literature on the same general topic. Both studies confirm that the introduction of horizontal inclusions of geosynthetic reinforcement can reduce footing displacements and increase footing bearing capacity compared to unreinforced foundation configurations. Neither paper addresses the issue of possible scale effects when attempting to extrapolate the results of small-scale tests (i.e. with prototype-scale reinforcement materials) to field scale.

3 STONE COLUMNS

3.1 *General*

Stone columns are used to improve foundation soils by increasing load support, reducing settlements and (or) increasing consolidation rates.

Table 2 shows that a total of 8 papers with the common theme of stone columns were submitted by authors from 8 different countries.

In the sections to follow the papers are grouped under the headings of case study, laboratory study and numerical modelling. The paper by Magnan et al. does not fall neatly into the categories selected. They discuss issues related to the influence of site investigation on stone column design and the influence of installation method.

3.2 *Case studies*

Dittrich et al. report the details of a project in the Barbados. Stone columns were used as vibro-replacement of a corraline soil located below a generator plant. The objective of the ground improvement was to reduce foundation settlements through densification of the highly variable soil deposits. The paper reports the use of SPT and cross-hole seismic testing used to characterize the soil before and after vibrodensification and replacement. Prior to installation of the stone columns, a pilot test program was carried out to confirm and quantify soil improvement using the proposed vibro-replacement method. Finally, the paper gives details of the results of the quality assurance programs using SPT and cross-hole seismic testing to ensure that target densification levels were achieved. The paper is an excellent example of a comprehensive case study that describes the site challenges, rationale for choice of ground improvement method, quality assurance testing methods and analysis of data.

The paper by Maurya et al. involves another power plant project, this time in India. Conventional slope stability analyses revealed that there was insufficient load support by the underlying soft marine clay without ground improvement. The paper is focused on the results of load testing of rammed stone columns at the embankment site. Load-settlement data are reported for single and multiple column configurations. The stone columns have performed as intended in the final ground improvement scheme.

3.3 *Numerical modelling*

A total of four papers in this session are focused on numerical modelling of stone columns.

Clemente et al. used a 3D FLAC program to carry out a parametric analysis of the influence of different square foundation configurations in combination with different soil properties. The relative benefits of the cases investigated are presented in terms of the ratio of the ground settlement for the modified foundation to the settlement of the unimproved ground, versus the stone column area replacement ratio. The influence of bearing pressure at the top of the foundation soil and stone columns is also introduced in the numerical modelling and demonstrated to be an important parameter that is not considered in current design methods. Numerical results are used to generate preliminary design charts to optimize the number and spacing of stone columns for foundation support over soils with more than 20% fines content.

Guetif Fessi and Bouassida used a poro-elastic axi-symmetric unit cell model to examine the settlement response of stone column foundations (vertical drains) in saturated soft clay. The results of analyses are presented as percent consolidation versus time of the improved soil zone (unit cell) and settlement versus time charts.

Pulko and Majes also use a unit cell approach to carry out settlement predictions of stone column groups. The parameters investigated include column spacing and length, initial ground stresses, material properties of the stone columns and soil, and applied load. The analytical method is shown to give good agreement with FEM analyses.

Tan and Oo show how the classical axi-symmetic unit cell problem for a single stone column can be converted to a two-dimensional plane strain problem for solution using FEM. The good agreement between both approaches is demonstrated using FEM codes. The plane strain model is used to predict the settlement response of an embankment case study and the agreement between predicted and measured settlement-time response illustrated. The practical benefit of the work is that computationally- and time-intensive 3D FEM modelling may be avoided using the 2D model approach.

3.4 *Laboratory testing*

A single paper in this session is focused on laboratory modelling of stone columns. Shroff and Patel describe small-scale tests carried out in a cylindrical container of a reconstituted soft kaolin clay. The stone column configurations investigated are identified as full length type, floating (reduced length), and composite (different bottom diameter with sand or the same stone material as in the upper section). Data are presented showing load-settlement response, and changes in the moisture content and shear strength of the surrounding soil. The relative benefits of the different configurations are noted.

4 CONCLUDING REMARKS

This session contains a wide range of papers on the topic of reinforcement of soil and soil structures, and stone columns. Many of the papers are of value to both practitioners in the form of case studies, as well as exposure to new analytical and numerical approaches to the solution of design problems involving reinforcement and stone column technologies. For researchers, there are valuable papers focused on laboratory testing, material properties and numerical modelling.

Finally, this reporter was impressed by the quality of the work presented by the authors and the care that was taken to present their work to the readers; for this, all authors are to be congratulated.

PAPERS IN TECHNICAL SESSION 2B

Aoki, H., Yonezawa, T., Tateyama, M., Shinoda, M., Watanabe, K. 2005. Development of aseismic abutment with geogrid-reinforced cement-treated backfill.

Bellezza, I., Pasqualini, E. 2005. Parametric study of the stability of slopes reinforced with piles.

Benjamim, C.V.S., Bueno, B.S., Zornberg, J.G. 2005. Comparison between field monitoring and numerical results of a woven geotextile-reinforced soil retaining wall.

Clemente, J.L.M., Senapathy, H., Davie, J.R. 2005. Performance prediction of stone-column-supported foundations.

Consoli, N.C., Casagrande, M.D.T., Coop, M.R. 2005. Behavior of a fiber-reinforced sand under large shear strains.

Davies, M.C.R., Morgan, N. 2005. The influence of the variation of effective stress on the serviceability of soil nailed slopes.

Dittrich, J.P., Boone, S.J., Hutchinson, A.E. 2005. Ground improvement in a coralline deposit in Barbados, W.I..

Freitag, N., Morizot, J.-C., Berard, G., Silveira Fernandes, K. 2005. Innovative solution for reinforced earth walls – Frictional connection.

Gualco, D., Berardi, R. 2005. Effects of geosynthetics reinforcement on bearing capacity and settlement of shallow foundations.

Guetif Fessi, Z., Bouassida, M. 2005. Settlement estimation of soils reinforced by columns using a poroelastic model.

Heitz, C., Kempfert, H.-G., Alexiew, D. 2005. Embankment project on soft subsoil with grouted stone columns and geogrids.

Justo, J.L., Durand, P., Soriano, C., Saura, J., Marco, J.M. 2005. Ground improvement and reinforcement in four dikes on soft soil.

Kim, N.K., Park, J.S., Jang, H.J., Kim, M.Y., Han, M.Y., Kim, S.B. 2005. A new IPS earth retention system.

Li, C., Zornberg, J.G. 2005. Interface shear strength in fiber-reinforced soil.

Magnan, J.P., Droniuc, N., Canépa, Y., Dhouib, A. 2005. Some thoughts about the design of stone columns.

Matsuoka, H., Muramatsu, D., Liu, S.H. 2005. Reduction of traffic-induced vibration by soilbags (“donow”).

Maurya, R.R., Sharma, B.V.R., Naresh, D.N. 2005. Footing load tests on single and group of stone columns.

Moraci, N., Recalcati, P. 2005. Pullout resistance of extruded geogrids embedded in a compacted granular soil.

Mulabdic, M., Minazek, K., Mrackovski, D. 2005. Influence of reinforcing grids on soil properties.

Patra, C.R., Mandal, J.N., Das, B.M. 2005. Ultimate bearing capacity of shallow foundation on geogrid-reinforced sand.

Pulko, B., Majes, B. 2005. Simple and accurate prediction of settlements of stone column reinforced soil.

Saramago, R.P., Ehrlich, M. 2005. Physical 1:1 scale model studies on geogrid reinforced soil walls.

Sayão, A.S.F.J., Lima, A.P., Springer, F.O, Nunes, A.L.L.S., Dias, P.H.V., Gerscovich, D.M.S. 2005. Design and instrumentation aspects of a 40m high nailed slope.

Shroff, A.V., Patel, B.R. 2005. Study on composite stone column in soft kaolinitic clay.

Stanic, B., Kovacevic, M.S., Szavits-Nossan, A. 2005. Parametric study of reinforced earth walls deformations.

Steenbergen-Kajabová, J., Steenbrink, R., Habib, H.A.A. 2005. Innovative restoration of medieval city walls of ‘s-Hertogenbosch by soil nailing.

Tan, S.A., Oo, K.K. 2005. Finite element modeling of stone columns - A case history.

Uchimura, T., Mizuhashi, M. 2005. Effects of reinforcement stiffness on deformation of reinforced soil structures under small cyclic loading.