History of Teaching and Research on Geosynthetics at I.I.T. Madras

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1. Introduction

The geosynthetics related activities at the Indian Institute of Technology Madras (hereafter referred to as IIT Madras) have started way back in mid 80's in a modest way. Prof. N. R. Krishnaswamy and Prof. T. S. Ramanatha Ayyar had paved the way for geosynthetics at the institute. They have initiated a new course titled "Reinforced Soil Structures" for post-graduate students of the geotechnical engineering program at the Department of Civil Engineering. Limited under-graduate and post-graduate student projects on the topics related to CBR value of reinforced subgrade, bearing capacity of reinforced soil beds were initiated. The laboratory facilities were limited to the direct shear and triaxial compression test machines and a few hand operated hydraulic jacks. The loads were measured using proving rings and the displacements were measured by the mechanical dial gauges. One continuing education program was conducted at IIT Madras with the support of ISTE and a booklet was published titled "Reinforced Soil Structures" in 1980's.

Since the inception, geosynthetic activities at the institute have expanded with time. Several masters and doctoral students have worked on geosynthetic related research topics. This write up provides a brief history of developmental activities pertaining to the geosynthetic materials at IIT Madras. It also describes the highlights of prominent research work carried out; important numerical & experimental facilities developed over the past decades, technical support extended to major industrial consultancy projects; geosynthetic relevant courses offered for undergraduate & postgraduate students, industry as well as to teachers of other engineering colleges.

2. Geosynthetics Related Educational Programs at IIT Madras

The educational programs on geosynthetics at IIT Madras started with a course titled "Reinforced Soil Structures" for the geotechnical engineering students in the latter part of the 1980's. This course was further expanded and the title was changed to "Geosynthetics and Reinforced Soil Structures" in the late 1990's with 40 hours of lectures. This has been offered continuously every year to the post-graduate students. The contents of this course include a brief history of geosynthetics, their manufacture and testing methods, design and construction of reinforced soil walls, embankments, foundations, flexible roads, landfills and filtration and drainage aspects. Typically about 30 to 35 post-graduate and senior level undergraduate students register for this course.

One major part of the course is the demonstration of the laboratory test methods pertaining to the geosynthetics. The test methods include determination of the index properties of the geosynthetics such as specific gravity, thickness, mass per unit area; strength properties of the geosynthetics using wide & narrow width tension tests, trapezoidal tear test, grab tension test, puncture strength test, dynamic cone penetration test; hydraulic properties like the apparent opening size, cross and in-plane flow tests and gradient ratio tests; connection strength between different types of wall panels and the geosynthetic reinforcement elements and interface properties between the geosynthetics and soil through pullout and modified direct shear tests.

Another course titled "Principles of Reinforced Soil Structures" has been introduced for the undergraduate students. This course is offered to the students as a regular 40 hour lecture course or as a self-study course with introductory lectures on each major topic in which a very elaborative course material handout is provided to the students. They are expected to read the material on their own and meet the teacher only for discussion and clarification of doubts. Typically about 30 to 40 students attend this course.

The geosynthetics and reinforced soil structures course has evolved with time and has resulted in a 40 hour video lecture course under the National Program on Technology Enhanced Learning (NPTEL) program which was uploaded to the NPTEL web site in 2013. These videos are freely available for download from the IIT Madras web site and through a video-sharing website YouTube. The interested students can post their questions and get clarification through e-mail.

More recently, an online certificate program has been initiated (July-November 2015) through the NPTEL office of IIT Madras. More than 2000 students from all over India and abroad have registered for this course. The students were given access to all the video lectures and specially prepared handouts for different lecture topics. The students are given weekly tutorials and one mid-semester examination and a final examination. All the examinations are completely computerised in view of the large number of students in the course. The final examination will be conducted at several centres all over India by M/s Tata Consultancy Services Ltd. on the similar pattern of GATE examination. The successful course participants will be awarded the course completion certificate by IIT Madras. In future, the students may be able to earn credits towards an academic

degree from IIT Madras upon successful completion of a series of related courses in an existing academic program.

Very recently, one new course titled "Barrier systems for waste containment" has been initiated. This course explores design concepts of various types of barrier systems, which are commonly used for containment of municipal as well as hazardous solid wastes. Course aims to enable the participants to design modern engineered barrier systems using an integrated approach, by considering the fundamentals of classical geotechnical engineering as well as concepts of interdisciplinary geoenvironmental engineering. The course also provides an in-depth knowledge pertaining to long-term performance of modern barrier systems under realistic scenarios, by understanding interaction between "waste-barrier-geomaterial". Very precisely, this course deals with an overview of barrier systems; composition of solid wastes; design of leachate collection system; fundamentals of contaminant transport; testing of materials; clay barriers (CB) and compatibility; geosynthetic clay liners (GCL); geomembrane liners(GM); design of cover liner systems.

3. Research Programs

The research work on geosynthetic related topics is performed through the student's thesis work of Master's and Doctoral level students and also through sponsored research projects. Till date, the topics of broad areas of research included the following:

- Reinforcement aspects of geosynthetics (geogrids and geocells)
- Creep behaviour of geosynthetics
- Reduction of earth pressures by use of compressible materials & geosynthetics
- Geosynthetic reinforced soil retaining walls
- Geosynthetic reinforced soil embankments
- Geosynthetic reinforced foundation soil
- Geosynthetic reinforced flexible pavements
- Geosynthetics for ground improvement
- Longevity of barrier systems
- Contaminant Transport through geosynthetic barrier systems

The list of the students and their thesis titles are shown in Table 1 and 2. The list of sponsored research projects taken up at IIT Madras along with the supporting organizations is illustrated in Table 3. A partial list of important journal papers that were published based on these works is listed at the end of the paper.

Table 1. List of Master of Science (MS by Research) Thesis and Master of Technology Project Titles

Name of the scholar	Thesis or project title	Year of award
Raghavendra, H.B.	Studies on Geosynthetics as Soil Reinforcement	1990
Parashar, S.P.	Experimental Investigations on the Uplift Behaviour of Plate Anchors with Geosynthetics	1992
Athavan, M.A.	Analytical and Experimental Investigations on Soil-Geosynthetic Composites as Foundation Beds	1995
S. Ramakrishna	Investigation on Application of Coir Reinforcement in Geotechnical Engineering	1997
V. Sri Hari	Investigation of the Behaviour of Retaining Walls Suppored by Vertical Plate Anchors	1997
Subramanyam Reddy	Investigation of the Behaviour of Helical Anchors Under Horizontal Loads	2000
Ramesh, G. V.	Studies on the Behaviour of Soil Nailed Retaining Walls	2001
Hari, S.	Behavior of fly ash under static and cyclic loading	2002
Sudhakar, S.	Analytical and Experimental Studies on Geotextile Reinforced Road Subgrades	2004
Mageshnagarajan, M.	Behaviour of reinforced soil foundation systems with anchors	2005
Srihari, K.	Finite Element Analysis of Reinforced Soil Walls Subjected to Seismic Excitation	2007
Maniraj, S.	Assessment of Concepts and Methodologies used for Design of Cover Systems for Waste Disposal Facilities	2010
Selvaganesh, S	Development of Rapid Methodology for Determining Diffusion Characteristics of Geomaterials and HDPE Geomembranes used in Engineered Landfill as Liner Material	2010
Ramesh, Gadela	Numerical Investigations on the Behaviour and Performance of Geocell Reinforced Foundation Beds Under Static Loading	2019

Table 2. List of Doctor of Philosophy Thesis Titles

Name of the scholar	Thesis Title	Year of award
Unnikrishnan, N.	Investigations on Reinforced Soil Embankments Subjected to Monotonic and Cyclic Loading	1998
Madhavi Latha, G.	Investigations on the Behaviour of Geocell Supported Embankments	2000
Dash, S. K.	Behaviour of Strip Footing Supported on Geocell Reinforced Sand Beds	2002
Jayalekshmi, S.	Studies on Geosynthetic Reinforced Retaining Walls	2004
Murugesan, S.	Geosynthetic Encased Stone Columns as Ground Reinforcement of Soft Soils	2008
Purnanandam, K .	Studies on Controlled Yielding Technique to Reduce Lateral Earth Pressure on Rigid Retaining Structures	2009
Sajna Sayed	Reliability Analysis of Reinforced Soil Retaining Walls using Conventional and Stochastic Finite Element Methods	2009
Anjana Bhasi	Performance Evaluation of Geosynthetic Reinforced Embankments Supported on Piles	2013
Ganesh Kumar, S.	Treatment of Soft Clay Deposits by Combined Encased Stone Column and Vacuum Consolidation	2014
Sridhar, G.	Some Studies On Preloading Of Soft Clay Deposits With Special Reference To Vacuum Preloading Technique	2015
Rejoice, A. A.	Longevity of Geosynthetic Material under Realistic Field Conditions	In Progress
Sunil Ranjan Mohapatra	Analysis of the Behaviour of Ordinary and Geosynthetic Encased Granular Columns Subjected To Shear Loading	2016
Nithin Sudarsanan	Investigations on the Control of Reflective Cracking in Flexible Pavements Using Geosynthetics	2018
J. Jayapal	Geosynthetic Encased Granular Column Treatment of Soft Clays: Numerical Analysis and Development of Design Charts	2021

Table 3. List of Sponsored Research Projects

Title of the Project	Duration	Sponsoring Agency
Studies on Geosynthetic Based Erosion Control Measures Along East Coast of India between Chennai and Sriharikota	April 2010 to April 2014	National Institute of Ocean Technology, Chennai
Investigations on Vacuum Consolidation of Soft Clay Deposits	April 2009 to March 2013	DST, New Delhi
Characterisation of Creep Response of Woven Geotextiles	July 2006 to April 2008	Garware Wall Ropes Ltd., Pune
Investigations on Modern Technologies for Construction of Road/Rail Embankments on Soft Clay	April 2005 to September 2008	MHRD, New Delhi
Investigations on the Anchored Retaining Walls for Railway and Highway Applications	April 1998 to October 2000	MHRD, New Delhi
Strength and stiffness of Geocell Reinforced Soft Soil Subgrades	April 1997 to May 1999	Netlon India Ltd Vadodara
Geosynthetics in Reinforced Earth Embankments	April 1995 to October 1998	DST, New Delhi

The above research projects have supported the laboratory development and providing financial support to the research scholars. Some large-scale field tests and laboratory based studies were performed on the use of geosynthetics. The deployment of a rope net gabion filled with geotextile sand bags is shown Fig. 1. Using this technology shore line stabilization has been demonstrated with the help of locally available beach sand and unskilled labour. The use of geocells for construction of experimental road bases in highly expansive soils and through desert soils is also demonstrated and the same is presented in the form of Figs. 2 and 3.

4. Some Major Consultancy Projects

The researchers at IIT Madras have provided consultancy services to several public and private sector industry for the construction of reinforced soil retaining walls, embankments, flexible road bases, engineered landfills, ground improvement works, etc. Some of these projects are briefly described in the following.

The faculty members from IIT Madras were involved in the design and construction of 70 m high reinforced soil embankment at the runway of Kannur International airport. The analysis and design was a challenging task due to difficult site conditions and heavy rain fall. Some pictures from the site that show the overall runway end safety area (RESA), drainage arrangement, toe wall built of gabions and vegetation for surface projection are shown in Figure 1.

Figure 1. Some pictures from Kannur International Airport

The construction of the first major hazardous waste landfill at Visakhapatnam was a big challenge as the entire landfill was built above the existing ground level. The construction of the embankment had to utilize the zerosite granules that are plentiful at the site. Large size direct shear tests were performed to determine the shear strength properties of this waste product mixed with different fractions of the local soil for deciding the optimum mix content and the compaction properties. The testing of the different varieties of geogrids, geotextiles, geomembranes and their joints had involved in developing much of the laboratory test facilities at the institute. The data required for the design and construction of the embankment was provided based on extensive laboratory tests performed at the institute. The unique connection strength apparatus that was developed with the help of industry support has been used extensively to recommend the connection strength between facing panels & modular blocks and different varieties of reinforcements. For several projects, the adequacy of the connection strength was verified using these facilities. Especially, the pullout capacity of steel and polymeric strips and method to enhance their pullout capacity by use of anchors was explored by several organizations with the help of this unique facility in the country. Some typical pictures from some of these tests are shown in Figures 2 to 9.

Fig. 2. Sand bag filled rope net gabions for shore line protection

Fig. 3 Geocell reinforced road base on highly expansive soil

Fig. 4. Geocell reinforced road in desert by Indian army

Fig. 5. Steel grids with a concrete block anchor

Fig. 6. Steel strips with end anchor

Fig. 7. Testing of positive connection

(a) View of the site *(b) Vacuum tube connected to PVD* *(c) Installation of PVD*

Fig. 8. Vacuum assisted pre-consolidation of soft clay soils

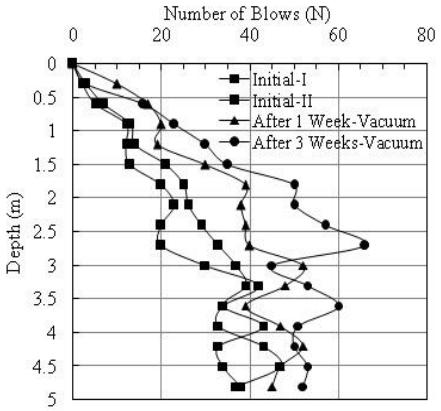

Figure 9. Strength of subsoil before and after vacuum treatment

5. Continuing Education Programs and Training

Several continuing education programs on the geosynthetics with 3 to 5 days duration were organised under the Quality Improvement Program of AICTE for teachers from different engineering colleges and under the Continuing Education Programs for practicing engineers. These courses are conducted periodically every alternate year over the past 30 years. On two occasions, these programs were conducted exclusively for the engineers from the railways to address challenges associated with railway embankments construction with geosynthetics. The lectures in these courses are delivered by faculty members from IIT Madras and other eminent engineers from private industry and other institutes. The total number of teachers/engineers trained under these programs is more than 500 over the past several years. A unique international training program titled Educating the Educators (EtE) sponsored by the International Geosynthetics Society was organized at IIT Madras in February 2019. The course faculty included both national and international academicians and practicing engineers.

6. Geosynthetic Testing Laboratory

The geosynthetic testing laboratory at IIT Madras has evolved with the growth of the research activities in this field. Initially, the facilities were quite limited owing to the paucity of funds. With the availability of sponsored projects and consultancy projects from private industry, the laboratory had undergone substantial improvements over the past 20 years. Some major facilities housed in the laboratory are listed below:

- Ultra Gas Pycnometer to measure specific gravity of geosynthetic material (Fig. 10)
- Geosynthetic thickness measuring apparatus (Fig. 11)
- Dog Bone Sample Cutter for tensile testing (Fig. 12)
- 150 kN Universal Testing Machine, UTM (Fig. 13) with computer controlled test and data acquisition. Using this apparatus along with different fixtures (wide width and narrow width grips for performing tensile strength tests on geogrids, geotextiles, geomembranes, grab tension tests, trapezoidal tear tests) the mechanical properties of various geosynthetic materials can be obtained.
- A 5 kN capacity UTM for testing of assessing the mechanical characteristics of very low strength geosynthetics such as wires, fibres (Fig. 14).
- 50 kN hydraulic servo-controlled cyclic test apparatus for performing model tests on soil structures with a large steel tank of plan dimensions 1.8m × 1.8m and height of 1.5 m (Fig. 15).
- CBR puncture test apparatus to obtain puncture strength of geotextiles and geomembranes (Fig. 16)

- 300 mm size direct shear apparatus for determining the interface properties and properties of coarse aggregates
- 60 mm size modified direct shear test apparatus to test the interface strength between geosynthetics and soil
- Large-scale test apparatus (1.5 m long × 1 m wide and 1 m height) to determine the pullout behavior of geosynthetics and connection strength between geosynthetic reinforcements and facing panels and facing blocks (Fig. 17).
- Geosynthetics accelerated creep testing apparatus (Fig. 18)
- In-plane permeability apparatus for geosynthetics
- Cross-plane permeability apparatus for geosynthetics
- Long term permeability and gradient ratio test apparatus
- Large-size puncture test apparatus to assess the burst strength of rope nets
- Gas Chromatography (Fig. 19)
- Flexible Wall Permeameter to determine hydraulic conductivity of GCLs (Fig. 20)
- Melt-Indexer (Fig. 21)
- Environmental Stress Crack Resistance Apparatus (Fig. 22)
- Sample Notcher for Environmental Stress Crack Resistance Test (Fig. 23)
- Gas Permeability Apparatus (Fig. 24)
- Apparatus for determining VOCs diffusion through geomembranes
- UV-Weatherometer (Fig. 25)
- Gas Diffusion Apparatus (Fig. 26)
- Medium size centrifuge for geotechnical testing (Fig. 27)
- Gas diffusion apparatus (Fig. 28)
- Vacuum pump for applying vacuum to soils
- Electronic Load cells, LVTDs, pressure cells
- Sieve test apparatus for determining the Apparent Opening Size of geotextiles
- Hydro-pneumatic system for applying constant pressure on large soil tanks
- Miniature electronic pore pressure and soil pressure cells
- Cone drop apparatus to assess the damage potential of geosynthetics

		
Fig. 10 Gas Pycnometer	**Fig. 11 Thickness Gauge**	**Fig. 12 Dog Bone Sample Cutter**
		
Fig. 13 UTM of 150 kN Capacity	**Fig. 14 UTM of 5 kN Capacity**	**Fig. 15 Servo-Controlled Cyclic Test Apparatus of 50 kN Capacity**
		
Fig. 16 CBR Puncture Test Apparatus	**Fig. 17 Apparatus For Determining Pullout Resistance**	**Fig. 18 Accelerated Creep Testing Apparatus**
		
Fig. 19 Gas Chromatograph to Determine Diffusion Properties of Geomembranes for VOCs	**Fig. 20 Flexible Wall Permeameter to Determine Sorption and Hydraulic Conductivity of GCLs**	**Fig. 21 Melt Indexer**

Fig. 22 Environmental Stress Crack Resistance Apparatus

Fig. 23 Sample Notcher for Stress Crack Resistance Test

Fig. 24 Gas Permeability Apparatus

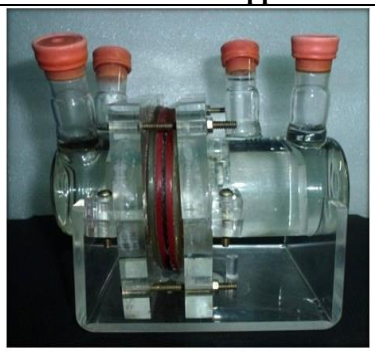

Fig. 25 Apparatus for Determining VOCs Diffusion through Geomembrane

Fig. 26 UV Weatherometer

Fig. 27 Mid-size centrifuge for model tests

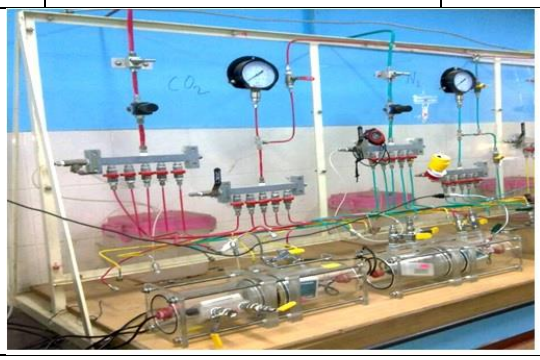

Fig. 28 Gas Diffusion Apparatus

7. Way Forward

The geosynthetic activities continue to pick up the momentum. Some new areas of research, especially on the control of reflection cracking in flexible pavements using natural and geosynthetic fibres, environmental applications, longevity studies of geosynthetics, diffusion studies on geosynthetics, application of geosynthetic in dams and canal lining works are taken up by the institute.

8. Related Published Papers

a) Featurted Articles in Professional Practice Magazines

1). Construction of High Geosynthetic Reinforced Soil Retaining Walls in India, The Master Builder, November 2014, 134-136.
2). Geosynthetics Lower Carbon Footprint, Infrastructure Today, August 2014, 12, No. 1, 54-56.
3). Stabilisation of Soft Clays using Vacuum Consolidation Technique, The Masterbuilder, Indian Construction Magazine, October 2008, 150-152.
4). Geosynthetic Encased Stone Columns for load support in soft clay soils, The Masterbuilder, Indian Construction Magazine, February, 2009, 88-92.
5). Modern Ground Improvement Techniques, Science and Technology Weekly Supplement of Hindu News paper April 1996.

b) Selected Technical Publications in Peer Reviewed Journal & Conferences

1. Krishnaswamy, N. R. and Raghavendra, H. B. (1989a). “Laboratory Evaluation of Geotextiles”, , International Workshop on Geotextiles, Bangalore.

2. Krishnaswamy, N. R. and Raghavendra, H. B. (1989b). "Evaluation of Soil-Geosynthetic Bond characteristics", International Workshop on Geotextiles, Bangalore 1989.
3. Krishnaswamy, N. R. and Parashar, S. P. (1991). "Uplift resistance of plate anchors with geosynthetics", Proceedings . of Indian Geotechnical Conference on Analysis, Practices and Performance, Surat, December, 337-340.
4. Krishnaswamy, N. R., Parashar, S. P. and Ramanatha Ayyar, T. S. (1991). "Effect of submergence on the uplift resistance of footings with geosynthetic inclusion", Proceedings of Indian Geotechnical Conference on Analysis", Practices and Performance, Surat, December, 333-337.
5. Krishnaswamy, N. R. and Parashar, S. P. (1992) "Effect of Strain Rate on uplift resistance of plate anchors with geosynthetics", Proceedings of International Symposium. On Soil Improvement and Pile Foundations, Nanjing, China.
6. Krishnaswamy, N. R. and Athavan, M. A. (1994). " The application of theory of elasticity for the analysis of reinforced earth beds", Second Annual Conference of Indian Society of Industrial and Applied Mathematics, February 23-25, Chennai, G1.1-G1.8.
7. Krishnaswamy, N. R. and Parashar, S. P. (1994). " Uplift behaviour of plate anchors with geosynthetics", Journal of . of Geotextiles and Geomembranes, Vol. 16, 67-89.
8. Krishnaswamy, N. R. and Athavan, M. A. (1997). "Stability Analysis of footings on reinforced sand, Proceedings of second Indian Institute of Science National Seminar on Geotechnical Engineering, Bangalore, Theme 7, Paper No. 32.
9. Rajagopal, K. and Sri Hari, V. (1998) "Experimental Investigation on Pullout Capacity of Vertical Anchors," Indian Geotechnical Journal, 28(2), 147-166.
10. Rajagopal, K. and Sri Hari, V. (1998) "Experimental Study on Retaining Walls Supported by Vertical Plate Anchors," Indian Geotechnical Journal, 28(3), 270-296.
11. Rajagopal, K., Krishnaswamy, N. R. and Madhavi Latha, G. (1999) "Behaviour of Sand Confined with Single and Multiple Geocells," Journal of Geotextiles and Geomembranes, 17(3), 171-184.
12. Krishnaswamy, N. R., Rajagopal, K. and Madhavi Latha, G. (1999). "Model Studies on Geocell Supported Embankments Constructed Over Soft Clay Foundation", Geotechnical Testing Journal 23(1), 45-54.
13. Dash, S. K., Krishnaswamy, N. R. and Rajagopal, K. (2001). "Bearing Capacity of Strip Footings Supported on Geocell-Reinforced Sand", Journal of Geotextiles and Geomembranes, 19, 235-256.
14. Dash, S. K., Rajagopal, K. and Krishnaswamy, N. R. (2001) "Strip footing on geocell reinforced sand beds with additional planar reinforcement", Journal of Geotextiles and Geomembranes, 19, 529-538.
15. Madhavi Latha, G., Dash, S. K., Rajagopal, K. and Krishnaswamy, N. R. (2001) "Finite Element Analysis of Strip Footing Supported on Geocell Reinforced Sand Beds", Indian Geotechnical Journal, 31(4), 454-478.
16. Rajagopal, K. and Ramakanth, P. L. S. (2001) "Finite Element Study of the Subsidence in Longwall Coal Mines", Journal of Rock Mechanics and Tunnelling Technology, 7(2), 93-111.
17. Unnikrishnan, N., Rajagopal, K. and Krishnaswamy, N. R. (2002) "Triaxial Behaviour of Reinforced Clay Under Static and Cyclic Loading", Indian Geotechnical Journal, 32(3), 216-234.
18. Unnkrishnan, N., Rajagopal, K. and Krishnaswamy, N. R. (2002). "Behaviour of reinforced clay under monotonic and cyclic loading", Journal of Geotextiles and Geomembranes, 20(2), 117-133.
19. Dash, S. K., Rajagopal, K. and Krishnaswamy, N. R. (2004). "Performance of different geosynthetic reinforcement materials in sand foundations", Journal of Geosynthetics International, 11(1), 35-42.
20. Madhavi Latha, G., Rajagopal, K. and Krishnaswamy, N. R. (2006)."Experimental and Theoretical Investigations on Geocell Supported Embankments", International Journal of Geomechanics, January-February 6(1), 30-35.
21. Murugesan, S. and Rajagopal, K. (2006). "Geosynthetic encased stone columns: Numerical Evaluation", Journal Geotextiles and Geomembranes, 24, 349-358.
22. Brachman, R. W. I., Rowe R. K., Take, W.A., Arnepalli, D. N., Chappel, M. J, Bostwick, L. E. and Beddoe, R. (2007). "Queens's Composite Geosynthetic Liner Experimental Site", 60th Canadian Geotechnical Conference, October 21-24, 2135-2142, Ottawa, Canada.
23. Dash, S. K., Rajagopal, K. and Krishnaswamy, N. R. (2007). "Behaviour of geocell-reinforced sand beds under strip loading", Canadian Geotechnical Journal, 44, 905-916.
24. Madhavi Latha, G. and Rajagopal, K. (2007). "Parametric finite element analysis of geocell supported embankments", Canadian Geotechnical Journal, 44, 917-927.
25. Murugesan, S. and Rajagopal, K. (2007). "Model Tests on geosynthetic-encased stone columns", Geosynthetics International, 14(6), 346-354.
26. Take, W.A., Arnepalli, D. N., Brachman, R. W. I. and Rowe R. K. (2007). "Laboratory and Field Calibration of TDR Probes for Water Content Measurement", 60th Canadian Geotechnical Conference October 21-24, 1865-1871, Ottawa, Canada.

27. Brachman, R. W. I., Rowe R. K., Arnepalli, D. N., Dickenson, S., Islam, Z., Sabir, A. (2008). "Development of an Apparatus to Simulate the Ageing of Geomembranes under Chemical Exposure Elevated Temperatures and Applied Stresses", The First Pan American Geosynthetics Conference & Exhibition, 2-5 March, 444-451, Cancun, Mexico.
28. Madhavi Latha, G., Dash, S. K. and Rajagopal, K. (2008). "Equivalent Continuum Simulations of Geocell Reinforced Sand Beds Supporting Strip Footings", Geotechnical and Geological Engineering, 26, 387-398.
29. Purnanandam, K. and Rajagopal, K. (2008). "Lateral Earth Pressure Reduction Due To Controlled Yielding Technique", Indian Geotechnical Journal, 38(3), 317-333.
30. R. Kerry Rowe and Dali Naidu Arnepalli. (2008). "The Effects of Landfill Temperature on the Long-term Performance of Composite Liners", 12th IACMAG, 1-6 October, Goa, India.
31. R. Kerry Rowe and Dali Naidu Arnepalli. (2008). "Theme lecture on Modelling the Effects of Aging of Geomembranes on Contaminant Transport and the Long-term Performance of Landfill Composite Liners", 12th IACMAG, 1-6 October, Goa, India.
32. Sajna S. Dodagoudar, G. and Rajagopal, K. (2008). "Analysis of Reinforced Soil Walls Under Static and Seismic Forces", Geosynthetics International, 15, 246-257.
33. Sajna Sayed, Dodagoudar, G. R. and Rajagopal, K. (2008). "Reliability Analysis of Reinforced Soil Walls", Indian Geotechnical Journal, 38(1), 49-67.
34. Jayalekshmi, S. and Rajagopal, K. (2009). "Failure surcharge pressures and FE Analyses of a reinforced retaining wall", Journal International Journal of Earth Science and Engineering, 2, 405-415.
35. Jayalekshmi, S. and Rajagopal, K. (2009). "Modelling of geosynthetics using True Findley and Onaran and Findley models", International Journal of Geotechnical Engineering, 3(3), 405-415.
36. Madhavi Latha, G., Dash, S. K. and Rajagopal, K. (2009). "Numerical Simulation of the Behaviour of Geocell Reinforced Sand in Foundations", International Journal of Geomechanics, 9(4), 143-152.
37. Murugesan, S. and Rajagopal, K. (2009). "Shear Load Tests On Stone Columns With And Without Geosynthetic Encasement", Geotechnical Testing Journal, 32(1), 76-85.
38. Sridhanya, K.V., Rajagopal, K. and Lakshmana Rao, C. (2009). "Modelling of Degradation of Clayey Soils under Repeated Loading", Indian Geotechnical Journal, 39(2), 139-152.
39. Bhasi, A. and Rajagopal, K. (2010). "Finite element study of the influence of pile jetting on load capacity of adjacent piles", International Journal of Geotechnical Engineering, 4(3), 361-370.
40. Boominathan, A., Rangaswamy, K. and Rajagopal, K. (2010). "Effect of non-plastic fines on liquefaction resistance of Gujarat Sand", International Journal of Geotechnical Engineering, 4(2), 241-253.
41. Kerry Rowe, R. Rimal, S. Arnepalli, D. N. and Bathurst, R. J. (2010). "Durability of Fluorinated High Density Polyethylene Geomembrane in the Arctic", Geotextiles and Geomembrane, 28, 100-107.
42. Kerry Rowe, R., Islam, M. Z., Brachman, R. W. I. and Arnepalli, D. N. (2010). "Antioxidant Depletion from an HDPE Geomembrane under Simulated Landfill Conditions", Journal of Geotechnical and Geoenvironmental Engineering, 136 (7), 930-939.
43. Murugesan, S. and Rajagopal, K. (2010). "Studies on the Behavior of Single and Group of Geosynthetic Encased Stone Columns", Journal of Geotechnical and Geoenvironmental Engineering, 136(1), 1-11.
44. Sajna, S., Dodagoudar, G. and Rajagopal, K. (2010). "Finite element reliability analysis of reinforced retaining walls", Geomechanics and Geoengineering, 5(3), 187-197.
45. Arnepalli, D. N. and Rejoice, A. A. (2012). "Durability and long-term performance of high density polyethylene geomembrane", ASCE Conference on Geosynthetic Lining Solution and Related Issues, Bangalore, 1, 72-91.
46. Arnepalli, D. N. and Rejoice, A. A. (2012). Durability and long-term performance of high density polyethylene geomembrane, ASCE Conference on Geosynthetic Lining Solution and Related Issues, Bangalore, 1, 72-91.
47. Bhasi, Anjana and Rajagopal, K. (2012). "A Comparative Study on the Performance of Piled Embankments with and without the Geosynthetic Reinforcement", Indian Journal of Geosynthetics and Ground Improvement, 1(2), 1-6.
48. Jayasree, K. P., Rajagopal, K. and Gnanendran, C. T. (2012). "Influence of Sidewall Friction on the Results of Small-Scale Laboratory Model Tests: Numerical Assessment", International Journal of Geomechanics, 12(2), 1-8.
49. Karthigeyan, S., and Rajagopal, K. (2012). "Influence of Rock Socketing on the Lateral Response of Single Pile", Indian Geotechnical Journal, 42(1), 49-55.

50. Rajagopal, K. and Murugesan, S. (2012). "Analysis and Design Methods for Encased Stone Columns", Chapter 30, Advances in Geosynthetics, Sai Master Environmental Services Pvt. Ltd., Hyderabad, 437-458.
51. Rejoice, A. A. and Arnepall, D. N. (2012). "Nanoindentation of high density polyethylene geomembrane", Proceedings of IGC-2012, New Delhi, 2, 798-801.
52. Bhasi, A. and Rajagopal, K. (2013). "Numerical investigation of the time dependent behaviour of geosynthetic reinforced piled embankments", International Journal of Geotechnical Engineering, 7(3), 232-240.
53. Bhasi, Anjana and Rajagopal, K. (2013). "Study of the Effect of Pile Type used for Supporting basal reinforced Embankments on Soft Clay", Indian Geotechnical Journal, 43(4), 344-353.
54. Anjana Bhasi and Rajagopal, K. (2014). "Geosynthetic-Reinforced Piled Embankments: Comparison of Numerical and Analytical Methods", International Journal of Geomechanics, DoI: 10.1061/(ASCE)GM.1943-5622.0000414.
55. Ewais, A. M. R., Kerry Rowe, R., Brachman, R. W. I. and Arnepalli, D. N. (2014). "Service Life of a High-Density Polyethylene Geomembrane under Simulated Landfill Conditions at 85 °C", Journal of Geotechnical and Geoenvironmental Engineering, 140 (11), 04014060.
56. Ganesh Kumar, S., Robinson, R. G. and Rajagopal, K. (2014). "Improvement of Soft Clays by Combined Vacuum Consolidation and Geosynthetic Encased Stone Columns", Indian Geotechnical Journal, 44 (1), 59-67.
57. Rajagopal, K., Chandramouli, S., Parayil, A. and Iniyan, K. (2014). "Studies on Geosynthetic Reinforced Road Pavement Structures", International Journal of Geotechnical Engineering, 8(3), 287-298.
58. Anjana Bhasi and Rajagopal, K. (2015). "Numerical study of basal reinforced embankments supported on floating/end bearing piles considering pile-soil interaction", Journal of Geotextiles and Geomembranes, In Press.
59. Arnepalli, D. N. and Rejoice, A. A. (2013). "Evaluation of Geosynthetic Liner Long-Term Performance under Landfill Conditions", Geopractices-2013, 3rd October, JNTU, Hyderabad.
60. Arnepalli, D. N. and Rejoice, A. A. (2013). "Service Life and Long-Term Performance of Geosynthetic Liners under Simulated Landfill Conditions", Geosynthetics India-2013, 23-25th October, New Delhi.
61. Brachman, R.W.I., Kerry Rowe, R. Arnepalli, D. N. and Andy Take, W. (2015). "Thermal exposure conditions for a composite landfill liner with a black geomembrane exposed to solar radiation", Geosynthetics International, 22(1), 93-109Dodagoudar, G., Sajna, S. and Rajagopal, K. (2015). "Random field modeling of reinforced retaining walls, International Journal of Geotechnical Engineering, 9(3), 229-238.
62. Ganesh Kumar, S., Sridhar, G., Radhakrishnan, R., Robinson, R. G., Rajagopal, K. (2015). "A Case Study of Vacuum Consolidation of Soft Clay Deposit", Indian Geotechnical Journal, 45(1), 51-61.
63. Nithin, S., Rajagopal, K. and Veeraragavan, A. (2015). "State-of-the Art Summary of Geosynthetic Interlayer Systems for Retarding the Reflective Cracking", Indian Geotechnical Journal, DoI: http://www.springer.com/-/6/AU76z_QmxIV6JZQW7JQh.
64. Rajagopal, K. and Arnepalli, D. N (2015). "State-of-the-Art on the Applications of Geosynthetics for Dam Repair and Rehabilitation", First National Dam Safety Conference, 24-25 March, 2015, IC&SR Auditorium, IIT Madras, Chennai, India.
65. Rajagopal, K., Jayapal. J. and Mohapatra. S. R. (2021) Geosynthetic-Encased Granular Columns Subjected to Vertical and Shear Loads, *Indian Geotechnical https://doi.org/10.1007/s40098-020-00486-4*.
66. Rajagopal, K. (2017) The Geosynthetics for Sustainable Construction of Infrastructure Projects, *Indian Geotechnical Journal*, Vol. 47, No. 1, 2-34.
67. Ramesh, G., Swetha, K., Sudersanan, N. and Rajagopal, K. (2021) Assessment of Load Distribution Mechanism in Geocell Reinforced Foundation Beds using Digital Imaging Correlation Techniques, *Journal of Transportation Geotechnics*, https://doi.org/10.1016/j.trgeo.2021.100664
68. Selvaraj, S. and Rajagopal, K. (2021) Numerical Analysis of Leutner Shear Tests on Interface Between Geosynthetic and Asphalt Layers, *Int. J. of Geosynthetics and Ground Engineering*, https://doi.org/10.1007/s40891-021-00295-6.
69. Ramesh, G., and Rajagopal, K. (2021) Laboratory and Numerical Studies on the Performance of Geocell Reinforced Base Layer Overlying Soft Subgrade, *International Journal of Geosynthetics and Ground Enineering*, https://doi.org/10.1007/s40891-020-00249-4.
70. Ramesh, G., and Rajagopal, K. (2020) Influence of pocket shape on numerical response of geocell reinforced foundation systems, *Geosynthetics International*, 1-11.

71. Jayapal, J. and Karpurapu, R. (2020) Bearing Capacity and Settlement Response of Ordinary and Geosynthetic Encased Granular Columns in Soft Clay Soils: Analysis and Design Charts. *Indian Geotechnical Journal*, 1-17.
72. Nithin, S., Arulrajah, A., Rajagopal, K. and Veeraragavan, A. (2020) Fatigue performance of geosynthetic reinforced asphalt concrete beams, *Journal of Materials in Civil Engineering*, Vol 32(8),
73. Jayapal, J. and Rajagopal, K. (2019) Settlement analysis of geosynthetic encased granular column treated soft clay deposits, *International Journal of Geotechnical Engineering*, Vol 14(3), 1-17.
74. Nithin, S., Arulrajah, A., Rajagopal, K. and Veeraragavan, A. (2019) Digital Image Correlation technique for Measurement of Surface Strains in Reinforced Asphalt Concrete Beams under Fatigue Loading, *Journal of Materials in Civil Engineering*, Vol 31(8), 1-10.
75. Reshma, B., Rajagopal, K. and Viswanadham, BVS. (2019) Centrifuge model studies on the settlement response of geosynthetic piled embankments, *Geosynthetics International*, Vol. 27(2), 170-181.
76. Jayapal, J. and Rajagopal, K. (2018) Encased Columnar Inclusions in Soft Grounds - A Review, *Geotechnical Engineering*, Vol. 49, 106-118.
77. Nithin, S., Rajagopal, K. and Veeragavan, A. (2018) An investigation on the interface bond strength of geosynthetic-reinforced asphalt concrete using Leutner shear test, *Journal of Construction and Building Materials*, Elsevier, Vol. 186, 423-437.
78. Nithin, S., Mohapatra, S.R., Rajagopal, K. and Veeraragavan, A. (2018) Use of natural geotextiles to retard reflection cracking in highway pavements, *Journal of Materials in Civil Engineering*, Vol. 30(4), 04018036.
79. Nithin S., Rajagopal, K. and Veeraragavan, A. (2015) Critical Review on the Bond Strength of Geosynthetic Interlayer Systems in Asphalt Overlays, *Japanese Geotechnical Society Special Publication*, Vol 2, Issue 67, 2296-2301.
80. Mohapatra, S.R. and Rajagopal, K. (2017). Undrained stability analysis of embankments supported on geosynthetic encased granular columns, Geosynthetics International, No. 5, Vol. 24, 465-479.
81. Mishra, S. R., Mohapatra, S.R., Sudersanan, N., Rajagopal, K. and Robinson, R.G. (2017). A Simple Image Based Deformation Measurement Technique in Tensile Testing of Geotextiles. Geosynthetics International, No. 3, Vol. 24, 306-310.
82. Mohapatra, S. R., Rajagopal, K. and Sharma, J. (2016) Direct shear tests on geosynthetic-encased granular columns, Journal of Geotextiles and Geomembranes, Vol. 44, 396-405.
83. Sridhar, G., Robinson, R.G. and Rajagopal, K. (2016) Properties of soil after surcharge or vacuum preloading, Proceedings of the Institution of Civil Engineers-Ground Improvement, Vol. 169, No. 3, 217-230.

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