

3D-Printed Modular Drainage & Cushion Units

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Abstract— Expansive soils, such as black cotton soil, present major challenges in civil engineering due to their high swelling and shrinkage behavior with moisture variations. These volume changes lead to severe foundation distress, uneven settlement, and structural cracking. Traditional stabilization methods using lime, cement, or chemical admixtures improve soil strength but are often time-consuming, environmentally harmful, and limited in long-term performance. To address this, the present study proposes an innovative 3D-Printed Modular Drainage and Cushion Unit (3DMDCU) system designed to control moisture variation and improve load distribution beneath shallow foundations.

The proposed system consists of lightweight, interlocking modular units fabricated using 3D printing technology. The modules integrate dual functionality: (1) a drainage network for controlled water flow and prevention of moisture accumulation, and (2) a cushion layer that redistributes stresses to minimize differential settlement. Smart materials, such as polymer composites and geosynthetic blends, are explored to enhance durability, permeability, and mechanical flexibility. By customizing unit geometry through parametric design, 3D printing enables optimization of hydraulic conductivity and compressive strength according to site conditions.

Experimental evaluation will involve laboratory-scale testing of soil-module interaction under varying moisture conditions, comparing settlement and swelling characteristics with conventional foundations. Numerical modeling using FEM (Finite Element Method) will also be conducted to analyze stress distribution and water flow through the printed modules. This study aims to demonstrate that 3D-printed modular drainage and cushion units can offer a sustainable, reusable, and adaptable alternative to conventional soil stabilization methods. The integration of additive manufacturing and smart drainage concepts can significantly reduce maintenance costs, improve long-term stability, and contribute to resilient infrastructure in expansive soil regions.

I. INTRODUCTION

Expansive soils, particularly black cotton soils, are one of the most problematic types of foundation materials encountered in civil engineering. These soils exhibit significant swelling when wet and shrinkage when dry due to the presence of montmorillonite clay minerals. Seasonal variations in moisture content cause repeated heaving and settlement of structures, leading to foundation cracks, wall distortions, and even structural failure. Conventional remedial methods such as lime stabilization, soil replacement, and under-reamed pile foundations have been widely used to address these issues. However, these solutions are often expensive, time-consuming, and less effective in controlling long-term moisture fluctuations around foundations.

In recent years, additive manufacturing (3D printing) has emerged as a transformative technology in civil engineering, offering high precision, flexibility, and design customization. The ability to produce lightweight, interlocking, and geometrically optimized components makes 3D printing ideal for geotechnical applications such as soil reinforcement and drainage systems. This project proposes a novel approach by introducing 3D-Printed Modular Drainage and Cushion Units (3DMDCU) beneath foundations to mitigate the adverse effects of expansive soils.

These modular units serve dual functions: (1) providing an effective drainage pathway to maintain uniform moisture conditions and prevent water accumulation, and (2) acting as a load-distribution cushion layer that reduces stress concentration and differential settlement. By integrating drainage control and load redistribution, the proposed system aims to achieve both stability and sustainability in foundation performance. Moreover, the use of recycled polymer materials and customizable 3D-printed designs support eco-friendly construction practices.

The research focuses on experimental testing and numerical simulation to assess the reduction in swelling pressure, settlement, and moisture variation. The ultimate goal is to develop a cost-effective, reusable, and innovative foundation support system suitable for expansive soil regions across India and beyond.

II. LITERATURE REVIEW

1. 3d-Printed Geocells in Footing Systems

Name of Author - S. Demirdöğen

Published Year - 2024

This experimental + numerical study investigates 3D-printed geocells used beneath footings and compares their performance to conventional geocells. Results show that customizable 3D-printed cells can be optimized for stiffness and permeability, improving bearing capacity and reducing settlement under both concentric and eccentric loads. The paper is useful for module geometry selection and demonstrates the feasibility of polymeric printed modules for load distribution in geotechnical applications.

2. Concrete 3d Printing Technology For Sustainable

Construction

Name of Author - X. Wang

Published Year – 2024

A broad review of 3D concrete printing trends, materials, and structural applications. Although focused on concrete, the review covers design optimization, parametric geometry for material efficiency, and on-site printing—concepts directly transferable to designing load-bearing printed modules and site-scale deployment of printed drainage cushions. Useful for thinking about on-site printing and material selection for larger modular units.

3. Emerging Trends in Expansive Soil Stabilisation A Review

Name of Author - C.C. Ikeagwuani

Published Year – 2019

Comprehensive review of expansive-soil problems and stabilization techniques (lime, fly ash, chemical, mechanical, drainage). Emphasizes that moisture control and drainage are among the most effective mitigation measures and that combining drainage with mechanical confinement (e.g., geocells) reduces swell pressures—giving theoretical backing to drainage-

cushion concepts. Also summarizes test methods for swell index and swelling pressure that you can use in the lab.

4. 3d Printing of Ecologically Active Soil Structures

Name of Author - S. Barnes et al.

Published Year – 2022

This work explores extrusion printing of soil/soil-like mixes to create stable soil geometries that support vegetation and control water retention. Key takeaways: printed cellular patterns strongly influence hydraulic behaviour and water retention, and tailored cell geometry can be used to regulate moisture movement a principle applicable to designing porous printed cushions that route water away from the active zone.

5. Evaluation Of the Structural Performance of the Geocell in Pavements

Name of Author - A. Khan

Published Year – 2023

Field and lab evaluations of geocells show significant improvement in pavement performance—reduced rutting and improved load distribution. The paper documents how geocell geometry and stiffness affect soil confinement and drainage behavior; these findings support using cell-like printed modules as engineered cushions beneath footings to both distribute load and create directed drainage paths.

6. Optimization Of 3d Printed Geocells Based on Numerical Simulation and Experimental Investigation

Name of Author - Amurane et al. / Arab et al.

Published Year – 2019

This collection of studies and experimental reports describes prototype 3D-printed geocells (PLA, PETG) and uses FEA + laboratory tests to tune wall thickness, cell shape, and infill for optimum stiffness/permeability. It provides practical guidelines on print settings, material behaviour, and how scale affects performance—directly relevant when designing modular drainage units for black cotton soil.

7. Insights Into 3d Printing of Polypropylene Geocells

Name of Author - P. Krishnaraj

Published Year – 2023

Chapter/paper focusing on manufacturing 3D-printed geocells in polymers (PP) with attention to geometry, joint details and fill interaction. Highlights manufacturing advantages (rapid prototyping, custom cross-sections) and limitations (UV degradation, creep) useful when selecting polymers and designing locking/interlock features for modular cushions intended for field use.

8. Interfacial Characterization of Soil-3d Printing Materials

Name of Author - S. Fadaie et al.

Published Year – 2024

This conference paper studies interfaces between soils and printed polymer components: adhesion, friction, and the effect of surface topology on drainage. Important for your project because module-soil interaction governs long-term performance (slip, clogging, and stress transfer). Recommends texturing and cell openings to improve soil-module drainage while minimizing clogging.

9. Foundation Piles—A New Feature for Concrete 3d Printers

Printers

Name of Author - M. Hoffmann

Published Year – 2021

Investigates the concept of printing foundation elements (including piles) and the structural considerations for printed concrete foundations. Offers insight on printed foundation components' structural design and integration—helpful for considering hybrid systems where printed cushion modules are combined with printed/ cast foundation elements for integrated solutions.

10. The Effects of Geocell Height and Lime Stabilization on Bearing Capacity

Name of Author - E.B. Pancar

Published Year – 2021

Laboratory work showing how geocell height and soil stabilization (lime) interact: taller cells and lime treatment both increase bearing capacity, while geocells improve drainage and confinement. The study supports a hybrid approach—combine printed modular cushions (for drainage & confinement) with local soil stabilization for best results in expansive soils.

III. SUMMARY

Recent research highlights the growing potential of 3D printing in geotechnical and construction engineering, particularly for developing customized geocells and drainage modules. S. Demirdöğen (2024) demonstrated that 3D-printed geocells beneath footings significantly improve bearing capacity and reduce settlement compared to conventional systems. Similarly, X. Wang (2024) reviewed sustainable 3D concrete printing technologies, emphasizing material optimization and on-site fabrication methods applicable to modular drainage units. Studies on soil stabilization, such as C.C. Ikeagwuani (2019), underline the importance of drainage and mechanical confinement to control swelling in expansive soils. Extending this concept, S. Barnes et al. (2022) showed that printed soil structures can effectively regulate moisture and hydraulic behavior through tailored cellular geometries.

Performance-based studies like A. Khan (2023) confirmed that geocell geometry and stiffness enhance load distribution and reduce pavement deformation, while Amurane et al. / Arab et al. (2019) optimized 3D-printed geocell design through experiments and simulations, providing guidance on wall thickness and shape for better stiffness and permeability. P. Krishnaraj (2023) discussed the fabrication of polypropylene geocells, identifying both benefits and challenges such as UV resistance and interlocking design needs. The work of S. Fadaie et al. (2024) highlighted the importance of soil–material interfaces, showing how surface texture influences drainage and stability.

Additionally, M. Hoffmann (2021) explored 3D-printed foundation piles, demonstrating the feasibility of integrating printed components into foundation systems. Finally, E.B. Pancar (2021) reported that increasing geocell height and using lime stabilization together improve bearing capacity and drainage efficiency. Overall, these studies establish that optimized 3D-printed geocells and drainage modules can enhance soil strength, control moisture, and enable sustainable, site-specific solutions for foundation and ground improvement applications.

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