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A New Method to Analyze for, and Design against, Translational Failures of Geosynthetic Lined Landfills

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This paper presents the recently developed method for translational failure analysis of landfills. Apparent cohesion of liner materials significantly increases the factor of safety, especially for a liner interface with a low friction angle and high apparent cohesion. Using an equivalent friction angle to represent the apparent cohesion of the liner materials is shown to lead to an unsafe result. Various leachate buildup conditions are analyzed for translational failures to simulate various conditions in wet, or bioreactor, landfills. The factor of safety for an interface with a high friction and low apparent cohesion generally drops much more quickly than that with inverse conditions when the leachate level is increased. This method can also be extended by using a pseudostatic approach to conduct seismic stability analysis. A liner interface with a low friction angle and high apparent cohesion has higher seismic resistance against an earthquake than one with a high friction angle and low apparent cohesion. It is also seen that the critical translational failure interface for a multilayer liner system cannot be simply assumed during seismic analysis. It can shift from one interface to another with changes of leachate level and seismic coefficient. Thus, each interface must be assessed accordingly.

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Applicability Evaluation of Geogrids in Reinforcement System

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Improved geogrids were manufactured to evaluate the applicability and long-term design allowable tensile strength from mechanical properties. For retaining wall and slope construction method, experimental construction and measurement were discussed and reanalyzed. We also evaluate and verify more systematically the properties and applications and construction stability of geogrids. Firstly, requiring properties and performance of domestic geogrids were introduced. We manufactured excellent creep behaviors geogrid with continuous manufacturing process system. Secondly, direct shear test and pull-out test are adopted to estimate frictional behavior of geogrid and long-term design allowable tensile strength of geogrids is estimated in accordance with GRI-GG4. Entire ranges of test methods are short-term tensile strength, tension creep behaviors, installation damage, and environmental durability to the chemical, thermal, and biological resistance. From the creep test results, woven geogrids represent excellent creep behavior within 10% of creep deformation under the conditions that 65% of ultimate tensile strength of geogrids. Finally, analysis of the reinforcement and construction details required to provide a retaining wall and steep slope were reviewed. In the results, from engineering design method, construction and measurement in the segmental retaining wall and steep soil-slope, application and construction stability of geogrids were verified.

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Behaviour of geogrid-reinforced sand subject to sustained loading in PSC

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The plane strain compression (PSC) tests, which can simulate typical field stress-strain conditions of reinforced soil structure (such as geogrid-reinforced soil retaining walls), are often performed on sand specimens reinforced with a wide variety of reinforcement to evaluate the tensile-reinforcing mechanism. Despite that it is well known that the strength of reinforced specimen increases by the so-called tensile reinforcing effects, little is known on the creep deformations of reinforced sand during sustained loading under constant boundary load conditions and the corresponding time histories of load and strain in the reinforcement that has viscous property. In the present study, sustained loading tests were performed on polymer reinforcement (e.g., a geogrid) alone during otherwise monotonic tensile loading as well as Toyoura sand (i.e., a fine quartz-rich poorly graded sand) alone during otherwise monotonic PSC loading to evaluate their viscous properties. Moreover, sustained loading tests were performed during otherwise monotonic PSC loading on a sand specimen (120 mm-high and 96 mm-wide in the average major and minor principal stress directions, respectively) reinforced with two layers of a polyester geogrid. In the longest sustained loading test lasting for 30 days, the sustained deviator stress, averaged for the specimen, was applied at the stress level about a half of the peak strength. It is shown that the creep deformation rate of the reinforced sand became nearly zero within an elapsed time of 30 days. The creep deformation of reinforced sand results from complicated interactions between elastic as well as visco-plastic deformations of both reinforcement and sand. In order to evaluate the local deformation of reinforced sand specimen (i.e., the local deformation of sand and reinforcement), a photogrametric analysis was performed on a number of photos of the transparent face of the specimen in the intermediate principal stress direction taken at a number of stages with known average stress, average strain and time in the PSC tests. A non-linear three-component rheology model, which is known to simulate very well the elastic-viscoplastic behaviours of geomaterials as well as polymer reinforcements, was used to evaluate the local tensile load-tensile strain behaviour of the geogrid during sustained loading of reinforced sand based on the time history of local tensile strains of the geogrid determined by the photogrametric analysis. The analysis indicated that the tensile force in the reinforcement decreased with time during the sustained loading at a constant load of the reinforced PSC specimen. It is usually assumed in design that the tensile load in the polymer reinforcement arranged in full-scale backfill is constant with time. The result from the present study suggests that the above may not be true and, therefore, the possibility of creep rupture failure of geogrid reinforcement arranged in the backfill of full-scale reinforced soil structure at typical working loads may be very low.

KEYWORD: Geogrid, Geogrid-reinforced sand, Plane strain compression, Photogrametric analysis, Viscous property, Non-linear three-component model, Simulation

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Combined fiber and geogrid reinforcement for foundation soil slabs

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Soil reinforcement is a practical solution to construction over weak soils. The concept of engineering a soil slab simultaneously reinforced with fibers and geogrid is developed. Such reinforcement appears to be quite effective, and well worth studying. Application of this concept is envisioned in construction of unpaved roads, temporary aircraft parking facilities, or when placing footings over weak soils. Layers of geogrid are placed in the fiber-reinforced fill to produce a slab capable of carrying large loads. To analyze the limit state of the slab, a model of fiber-reinforced soil is used first to determine the properties of the fiber-reinforced fill. The contribution of the geogrid to the strength of the slab is then determined by considering two possible modes of failure: slip and tensile rupture. The framework of the kinematical approach of limit analysis is used to arrive at loads that would produce a failure of the slab. The slab can be constructed over weak clay or loose sand. The thickness of the slab, fiber content, and the number of geosynthetic layers and their strength are to be determined from the analysis. The preliminary results will be used to formulate provisional design guidelines.

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Comparing zigzag arrangement to rectangular arrangement of geotextile-reinforced soil wall

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Use of geotextile-reinforced soil walls is growing rapidly. However, while the current design technique stipulates a 2D geotextile positioning method, there are no has much research been conducted on the subject. As a first step to establishing the optimal 3D positioning method, we conducted load tests, examining the mechanism of 3D reinforcement and using 3D finite element method analysis to verify the results. Two positioning methods were tested, a rectangular arrangement and a zigzag arrangement. The results of experiments and verification by analysis showed that, compared to a rectangular arrangement, a zigzag arrangement better contains warping, etc., by reducing shear strain and suchlike in the reinforcement fill and thus enhancing the stability of the reinforced soil wall.

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Constitutive Modeling of the Time-Dependent Monotonic and Cyclic Behavior of Geosynthetics

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Permanent geosynthetic-reinforced soil structures were subjected to the effects of creep and/or stress relaxation due to the time-dependent behavior of geosythetic inclusions and probably soil. The dynamic behavior of the geosynthetic-reinforced soil structures are then greatly influenced by the strain-rate dependent cyclic behavior of the geosynthetic reinforcements that have experienced long term of creep or stress relation. In order that the time-dependent monotonic and cyclic behavior of geosythetics can be properly simulated, a constitutive model that is based on the theory of visco-plasticity as well as empirical formulations is formulated in this paper. The model utilized the concept of internal state variables and was constructed based on the available experimental results of geosynthetics. It is also developed in a hierarchical manner so that it can be employed in different applications. The model was evaluated using creep, stress relaxation, and cyclic experimental results of different geosynthetics.

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Design Framework for Geosynthetic Reinforced Earth Structures

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Current design of geosynthetic reinforced earth structures is either based on lateral ‎earth pressure theories (walls) or limit equilibrium analysis (slopes). The approaches ‎are incompatible and, consequently, national design guidelines define walls as having a ‎slope steeper than 70 degrees while slopes are inclined at 70 degrees or flatter. ‎Obviously, the 70 degrees limit is arbitrary and is used mainly due to historical reasons. ‎The economic and aesthetics of geosynthetic walls are appealing and, as a result, it is ‎increasingly being used in complex geometries for which the existing theories of lateral ‎earth pressure are no longer valid. Conversely, limit equilibrium analysis can deal with ‎a wide range of boundary conditions. It is a common design tool in geotechnical ‎engineering and, if properly applied, it can be used in the design of walls; i.e., be used ‎for all geosynthetic reinforced earth structures. However, there are some details that ‎first need to be explicitly resolved. One such item is the required connection strength ‎between the reinforcement sheet and the facing unit. ‎

Presented is general approach using limit equilibrium analysis that accounts for ‎connection strength, rear-end pullout of reinforcement, reinforcement length, spacing, ‎as well as various boundary conditions and loading. The notion of safety map is ‎employed in which for selected soil strength, the required reinforcement strength is ‎determined rigorously along the length of each layer considering rear-end and front-end ‎pullout resistance. The interaction of soil-geosynthetic and layer to layer is considered ‎in this analysis. One can use in this framework any type of limit equilibrium analysis. ‎However, to demonstrate its application for walls, the simple Culmann method (planar ‎slip surface combined with a close-form solution) is used.‎

Effects of Geosynthetic Reinforcement on Soil-Pipe Interaction

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Pipelines are shallowly buried in the ground. As a consequence, they are liable to damage by the traffic loading. Geosynthetic reinforcements are installed above the pipe so as to modify the stress conditions in improving the pipe performance. A series of model tests were conducted followed by simulation using the finite element method. In the model test, a flexible HDPE pipe was buried in Nevada sand. Cases of unreinforced and reinforced soil-pipe system were tested. A polyester geogrid was used as reinforcement, in which the total number of layers and lengths were varied.

Geosynthetics to the Rescue

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While this symposium honors Dr. Koerner's achievements in geosynthetics research, it must be remembered that his research originated in and continues today with solving practical problems of the engineering and construction communities by using geosynthetics. It is therefore fitting that some practical applications resulting from his work be studied to show how geosynthetics have allowed solutions to field situations that would otherwise have been expensive or virtually impossible.

The examples in this paper illustrate the use of geosynthetics in south Louisiana and coastal Mississippi, which have some of the largest deposits of soft, highly compressible deposits in the United States. The major application has been reinforcement of soft soils which were incapable of supporting the design loads or earthwork construction without serious modification. For example, geogrids plus sand allowed compaction of a landfill liner on very soft clays 20 feet below groundwater level. Geogrids and geowebs have been used to allow underwater fill placement at port facilities, plus subgrade stabilization for railroad spurs and road construction. An interesting application has been for supporting the bases of large cranes for heavy industrial lifts, a situation where both strength and deformation are critical. The analyses for crane lifts used classical multi-layer soil models, plus Koerner's methods for analysing the geosynthetic reinforcement. The measured deformation behaviours compared quite closely with those predicted. Geosynthetics are also employed in this area for drainage media and hydraulic or contamination barriers. For example, geosynthetics are far superior to granular soils for the leachate drainage layer on the sides of landfill excavations. The examples of these uses given herein show that geosynthetic solutions have proven cost-effective, rapid, and relatively simple to install.

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Mathematical Modeling of Polymeric Reinforcement: Current Practice and Future Trends

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Soil is an abundant construction material that, similar to concrete, has high compressive strength but virtually no tensile strength. To overcome this weakness, soils, like concrete, may be reinforced. The materials typically used to reinforce soil are relatively light and flexible, and though extensible, possess a high tensile strength. Examples of such materials include thin steel strips and polymer materials commonly known as geosynthetics. When soils and reinforcement are combined, a composite material - the so-called "reinforced soil" - possessing high compressive and tensile strength (similar in principle to reinforced concrete) is produced. This combined high strength is attributed primarily to the frictional interaction between the soil and the reinforcement. The extra strength means that, for example, a bridge abutment made of reinforced soil will bear higher loads than an unreinforced one, or that reinforced slopes can be constructed at steeper angles as compared to unreinforced ones.

It is well known that polymers exhibit time-, strain-rate and temperature-dependent behavior. To mathematically represent this complex mechanical behavior requires an accurate model of the geosynthetic. Numerous mathematical models of the geosynthetics, possessing varying degrees of sophistication, have been developed over the past twenty-five or so years. More recently, due to the increased use of polymers in a broad range of applications (e.g., aerospace, automotive, electronic systems, etc.), the micromechanics based characterization of deformation mechanisms and the modeling of the viscoelastic-viscoplastic and elasto-viscoplastic behavior of polymeric materials have received considerable interest. Not surprisingly, a number of advanced constitutive models have been developed to characterize the time-dependent mechanical behavior of polymeric materials. In this paper, an overview of general classes of models used to characterize polymeric reinforcement is provided. In addition, the suitability of the more advanced mod-

els for simulating the time-, strain-rate and temperature-dependent behavior of commonly used polymeric reinforcement is investigated. The trade-offs between model sophistication, predictive capabilities and simplicity are discussed.

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SEISMIC RESPONSE ANALYSIS OF FULL-SCALE REINFORCED SOIL RETAINING WALLS

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Numerical simulation using finite element procedure was conducted on three full-scale models of geosynthetic-reinforced soil structures. The walls were the tallest of their kind at 2.8 meters. They were subjected to Kobe earthquake motions that were scaled to an acceleration amplitude of 0.4g and 0.8g. In the analysis, the block facing and the EPS board at the boundaries were modeled as linear elastic materials, the geosynthetic reinforcement was modeled using a bounding surface model of power hardening functions, and the backfill and foundation soil were modeled using a generalized plasticity model. This generalized plasticity model was able to describe the pressure dependent and cyclic hardening behavior of sand. The results of simulation, including wall facing deformation, crest settlement, acceleration in the backfill and geogrid tensile force were compared. It was found that this finite element procedure was able to simulate the seismic response of the reinforced soil retaining walls.

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The design and construction of mechanically reinforced earth walls reinforced with polymeric reinforcement

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Mechanically stabilized earth walls with discrete panels were first used to construct retaining walls in France in the nineteen sixties. This type of construction is now widely used to construct retaining walls and bridge abutments, primarily as they offer greater flexibility in construction, better resistance to static and dynamic loadings, significant cost savings and an attractive and varied appearance. Mechanically stabilized earth structures consist of reinforced concrete panels which are anchored into the soil immediately behind by reinforcement strips. Early structures used metallic strip but by the nineteen seventies polymeric strips were also being used due to their higher resistance to environmental attack. Today polymeric reinforcement is widely used across Europe, the Middle East and Asia in the construction of mechanically stabilized earth walls.

In the late nineteen seventies extensive research on the short and long term performance of polymeric reinforcement in mechanically stabilized earth walls was initiated. The performance of an instrumented polymeric wall constructed by the Transport Research Laboratory (TRL) in the UK is presented. Studies on the effects of temperature, creep and environmental degradations of the properties of the polymeric reinforcement are also reported. Based on these studies, the long terms behavior of the polymeric reinforcement in mechanically stabilized earth walls is now well understood.

This paper details the extensive experimental data available on the performance of mechanically stabilized earth walls reinforced with polymeric reinforcement.

The difference in design approaches (BS 8006) is also examined; the inextensible metallic reinforcement is normally designed using the coherent gravity method while the extensible polymeric reinforcement uses the tie back wedge method although some polymeric materials have been shown to behave in an inextensible manner. The paper shows where this is appropriate.

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VALIDATION OF NUMERICAL MODELS FOR STATIC AND SEISMIC ANALYSIS OF REINFORCED SOIL WALLS

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The structural response of geosynthetic reinforced-soil (GRS) retaining walls to static and dynamic loading conditions is complicated by the load-strain-time properties of polymeric reinforcement materials and the interactive effects between their soil, reinforcement and facing components. As a result, analytical methods for their analysis and design that have historically been adapted from those commonly used for conventional retaining walls often do not lead to accurate predictions of wall behaviour. Recent studies by the authors have shown that current limit equilibrium-based practice for design of GRS walls in North America is excessively conservative and needs to be replaced by more advanced design methodologies that are based on better understanding of the mechanical response of GRS walls subjected to different loading conditions. As a result, the authors and co-workers have undertaken a long-term research programme that involves the construction and monitoring of carefully instrumented large-scale geosynthetic (and metallic) reinforced soil retaining walls built within a controlled laboratory environment. This on-going research is aimed at generating high-quality and comprehensive data that can be used to verify advanced numerical models of reinforced soil walls, which can subsequently be used to extend the limited database of laboratory and field case studies to a wider range of wall

types, component materials and configurations.

The paper provides a brief overview of numerical models recently developed by the authors for the analysis of reinforced soil walls under static and seismic loading conditions. The models adopted for the component materials are described and sample numerical analysis results are presented. The numerical results have consistently shown satisfactory agreement with measured wall response parameters. The combination of validated physical and numerical test results can be used to check or refine recently proposed analytical design methods for geosynthetic reinforced soil wall structures that hold promise to make these systems more cost effective.