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Evaluating reinforcement loading within surcharged segmental block reinforced soil walls using a limit state framework

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A B S T R A C T

Internal design of Mechanically Stabilized Earth (MSE) Walls are frequently based on lateral earth pressure methods. A key component of limit state design includes determination of the necessary resisting forces of reinforcements to enable stability and function of the internal reinforcing components. However, conventional methods (e.g. Rankine) are not directly applicable when accounting for surcharge loading that is non-uniform, often manifested by the presence of strip footings placed directly on the reinforced soil. Within this study, an approach is presented to determine the reactive loads in individual reinforcements, T_{max}, using limit analysis (LA) considering a log-spiral mechanism and the effects of facing elements for segmental block reinforced soil walls. Lateral earth pressures attained from this approach are consistent with simplified analyses presented in the literature, realizing reinforcement loads that are more reasonable when compared with observed reinforcement loading than conventional limit equilibrium-based methods. To demonstrate the effects of various design parameters, the relationship between soil strength properties, interface friction between the soil, facing and toe, wall height, wall batter and reinforcement loads were studied.

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1. Introduction

Design of Mechanically Stabilized Earth (MSE) walls requires that checks for both internal and external stability are made for the reinforced structure to ensure satisfactory resistance against collapse (ultimate limit state). Internal stability is characterized by determining the maximum reinforcement loading and designing against reinforcement rupture, connection failure or pullout failure, typically determined based on expected earth pressure during service (AASHTO, 2012; NCMA, 1997). These approaches assume that lateral earth pressures are known based on simplified earth pressure approaches (e.g. Rankine earth pressure distribution), which yields maximum tension, T_{max}, for each reinforcement based on its tributary area.

Frequently, spread footings are built on reinforced soil, such as superstructure support in bridge abutments. However, the resulting lateral earth pressures are not easily determined under a discrete surcharge applied by a rigid footing due to the dissonance between footing design and MSE wall design. However, the presence of a non-uniform surcharge atop a reinforced soil structure does necessitate a synthesis of the footing effects as it can increase reinforcement loading and affect internal stability. A non-trivial problem, most approaches to quantify the effect of spread footings on earth pressures have been limited to empirical and simplified elastic approaches (e.g. Spangler, 1939; Poulos and Davis, 1980) or complex Finite Element or Finite Difference models (e.g. Hatami and Bathurst, 2006; Helwany et al., 2007; Ehrlich and Mirmoradi, 2013; Ambauen et al., 2015). Jackson (1985) proposed the Incremental Mirror Method (IMM) using the 2:1 method and superposition to determine vertical pressures beneath the strip footing adjacent to the edge of reinforced soil structure which demonstrated to be a reasonable when compared to other alternative techniques (Jackson and Jones, 1988). However, elastic theory cannot always accurately predict reinforcement loads and requires an assumption of ‘rigid’ or ‘flexible’ facing conditions. Complex numerical models that capture accurate reinforcement loading require realistic constitutive models and knowledge of material deformation properties, which can be difficult to quantify. Moreover, both analyses commonly focus on service state

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conditions while not fully accounting for limit state conditions (i.e. fully plastic conditions).

Prior research has often focused on the service state conditions of reinforced soil supporting spread footings as excessive deformations may compromise superstructure functions (e.g. settlement, facing movement, "bump" at the bridge) – phenomena that are commonly dominated by foundation conditions (Jones and Edwards, 1980). Existing literature primarily includes physical experiments in both the field and laboratory, typically limited to observations on service state behavior. Huang and Tatsuoka (1990) performed experimental studies on bearing capacity of shallow foundations placed upon sand reinforced with layers of geosynthetic reinforcements. Full-scale experiments were also conducted to evaluate serviceability of geosynthetic reinforced soil (GRS) structures supporting surcharge loading (Wu et al., 2001; Bathurst et al., 2003; Yoo and Kim, 2008). Hatami and Bathurst (2006) evaluated the performance of reinforced soil segmental under surcharge loading with both experimental results from large-scale laboratory tests and subsequent numerical modeling (Finite Difference), finding agreement for service-state conditions. Helwany et al. (2007) performed finite element analyses of MSE wall-supported abutments, evaluating the deformation of the wall under a surcharge with varying vertical reinforcement spacing, reinforcement types and backfill soils. Yoo and Kim (2008) modeled the behavior of a two-tiered MSE wall under surcharge loading using three-dimensional analyses with finite element analysis.

Evaluation of limit state conditions within a reinforced soil structure is critical as it often mandates selection of structural elements and construction materials. Limit state conditions are often determined using limit equilibrium (LE) or limit analysis (LA) methods, which both evaluate forces within a system at the brink of collapse. Blatz and Bathurst (2003) used a conventional two-part wedge limit equilibrium method to predict the ultimate capacity of a footing placed close to the crest of reinforced structures. Jahanandish and Keshavarz (2005) presented a new approach based on the slip-line method and analyzed bearing capacity of footing placed on reinforced structures with uniform and non-uniform distribution of reinforcement. Ausilio (2014) developed an upper bound framework to calculate seismic bearing capacity of strip footings surcharged on geosynthetic reinforced soil structures. Several studies have focused on using limit analysis to evaluate ULS conditions for bearing capacity atop reinforced soil (Xie and Leshchinsky, 2015; Leshchinsky, 2014).

Within most limit state analyses, the impact of structural facing elements were ignored for simplification, primarily evaluating earth pressures and respective reinforcement loading. Typical MSE wall design involves assumed earth pressures (usually Rankine) for internal design of reinforcements, but structural properties of the facing elements are frequently ignored. These effects, however, are considered implicitly in some codes (e.g. NCMA, 1997) and the design of proprietary facing block systems, particularly in context of connection strength. Special consideration should be given to the effects of segmental block wall facing as performance issues, like differential settlements, poor compaction, excessive movement at the toe and incorrect installation may compromise the structural effects of facing elements. These elements may play a significant role in earth pressures and reinforcement loading due to downdrag, especially in consideration of toe resistance (Leshchinsky and Vahedifard, 2012). However, downdrag also requires differential settlement of backfill material and a facing column – a process that is difficult to predict and may result in higher connection loads and possible poor wall performance. Use of sufficiently small vertical spacing or intermediate reinforcement layers may mitigate deleterious connection loads (Leshchinsky et al., 2014). Facing elements, such as modular blocks, are considered in several experimental and numerical simulations (Hatami and Bathurst, 2006; Bathurst et al., 2006, 2007) as they play a significant role in wall behavior, especially under surcharge loading. Use of limit state methods, like limit analysis, may provide a more comprehensive evaluation of the complex interaction between backfill soil, reinforcement, and structural facing elements. One such approach to synthesize these parameters in internal design is the "top-down" approach (Leshchinsky et al., 1995), which uses the log-spiral mechanism to determine reinforcement loading in an iterative scheme. The top-down approach was adopted to calculate reinforcement loading at elevations along a MSE wall face to account for internal design, but block weights and spread footings were not accounted for. Baker and Klein (2004) substantially modified the top-down approach and accounted for the facing by considering its shear and bending resistance, but did not account for spread footing support. This approach may be refined to account for structural interactions, including facing-backfill friction, block—-block friction, block weight, toe friction and non-uniform surcharge loads.

To evaluate the effects of interaction amongst backfill, blocks, and the toe of surcharge reinforced soil walls on internal stability, a top-down approach based on upper bound limit analysis was applied. This approach considers the effects of interaction between structural materials, providing an estimate that accounts for both facing effects and/or the presence of a spread footing. Results attained from this approach are compared with other analytical solutions, showing adequate agreement. A parametric study is carried out to investigate the influence of various parameters on reinforcement loading. The effects of toe resistance and interface friction on reinforcement load distribution may have a notable influence on internal stability of MSE walls; however, extreme caution should be exercised in its consideration in design as toe resistance should not be considered unless the foundation material is competent (rock), particularly when supporting a surcharge (CIRIA, 1996).

For geosynthetic reinforced soil structures using segmental facing elements, internal stability design considerations must be made for reinforcement strength, pullout and connection – this analysis focuses on determining required reinforcement strength along a given wall profile. Previous literature has described pullout resistance between geosynthetics, particularly geogrids, to be dependent on soil particle size relative to the apertures in the geogrid (Lee, 2000), often demonstrating high bearing and frictional interlock when apertures were adequately sized (Jewell, 1990). When sufficient interlocking behavior occurs between a geogrid and soil is realized, pullout may be inhibited with sufficient interlock. In this case, shear strains may propagate in the soil adjacent to the reinforcement instead of at the soil-geogrid interface, demonstrated experimentally (Boyle, 1995; Bathurst and Ezzein, 2016) and frequently applied numerically (Hatami and Bathurst, 2005; Yoo and Kim, 2008; Ambauen et al., 2015) for geosynthetic reinforced soil structures. Connection strength is an important design consideration for segmental walls, particularly when vertical spacing between reinforcements is large; however, with proper construction practices (i.e. compaction) and sufficiently small vertical reinforcement spacing, connection issues may be mitigated (Soong and Koerner, 1997). Under the assumption that connection strength was sufficient and pullout was not likely, this analysis focused on required reinforcement strength of geosynthetic reinforcements alone.

2. Model description

MSE Walls are frequently built with block facing elements atop a leveling pad with non-structural properties for constructability purposes. Governing design parameters include wall batter, ω; wall

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