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Reliability-based load and resistance factor design approach for external seismic stability of reinforced soil walls

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A B S T R A C T

Load and resistance factor design (LRFD) approach for the design of reinforced soil walls is presented to produce designs with consistent and uniform levels of risk for the whole range of design applications. The evaluation of load and resistance factors for the reinforced soil walls based on reliability theory is presented. A first order reliability method (FORM) is used to determine appropriate ranges for the values of the load and resistance factors. Using pseudo-static limit equilibrium method, analysis is conducted to evaluate the external stability of reinforced soil walls subjected to earthquake loading. The potential failure mechanisms considered in the analysis are sliding failure, eccentricity failure of resultant force (or overturning failure) and bearing capacity failure. The proposed procedure includes the variability associated with reinforced backfill, retained backfill, foundation soil, horizontal seismic acceleration and surcharge load acting on the wall. Partial factors needed to maintain the stability against three modes of failure by targeting component reliability index of 3.0 are obtained for various values of coefficients of variation (COV) of friction angle of backfill and foundation soil, distributed dead load surcharge, cohesion of the foundation soil and horizontal seismic acceleration. A comparative study between LRFD and allowable stress design (ASD) is also presented with a design example.

1. Introduction

Current design practice of reinforced soil retaining walls is based on the limit equilibrium approach. The walls are designed for both external and internal stability criteria. There are several possible failure modes considered in the design of reinforced soil retaining walls to satisfy both external and internal stability. The reinforcement length is governed by the external stability conditions and the vertical spacing of reinforcements is governed by the internal stability conditions. Further, design of the wall should be such that minimum required safety factors are fulfilled for all failure modes under static as well as earthquake loading. The major design considerations for a reinforced soil structure are the stability assessment of the potential external failure modes of the wall. The design earthquake imposes several types of dynamic loads on the structure. The greatest dynamic load is the inertia load caused by the response of the backfill soil to ground motion accelerations.

Many studies are reported in the literature regarding the seismic stability analysis of reinforced soil structures based on a pseudo-static limit equilibrium analysis (Bathurst and Cai [1], Ling et al. [2], Ling and Leshchinsky [3], Ismeik and Guler [4], Basha and Basudhar [5]). An important issue in the evaluation of seismic stability of reinforced soil structures is the lack of exact knowledge of strength parameters of the backfill and foundation soil parameters. Since there are many uncertainties in backfill and foundation soil properties, the analysis from the probabilistic point of view is needed. An effort has been made in this direction by Chalermyanont and Benson [6] who conducted a reliability study on the external stability of mechanically stabilized earth walls in static conditions. Basha [7] and Basha and Babu [8] reported a study on reliability based design optimization of external seismic stability of reinforced soil structures under earthquake loading using pseudo-dynamic method. Again, using similar pseudo dynamic approach, Basha and Babu [9] presented a methodology for reliability assessment seismic internal stability of reinforced soil structures using logarithmic spiral failure mechanism by taking into account three failure modes such as tension failure, pullout failure and total pullout failure. In addition, Basha and Babu [10] reported seismic external stability analysis of geosynthetic reinforced soil walls by taking into account the effect of uncertainties using target reliability based approach (TRA) considering three modes of failure such as sliding, bearing and overturning or eccentricity failure.

Seismic design of a mechanically stabilized soil structure subjected to earthquake ground motions requires explicit satisfaction of multiple performance criteria such as sliding stability, eccentricity (or overturning) stability and bearing capacity stability modes.

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Notations

$A_{\max}$	peak horizontal ground acceleration coefficient
c	cohesion of the foundation soil
e	eccentricity of the resultant force
$f_X(x)$	is a joint probability density function of X
FS_{sli}, FS_b	factor of safety against sliding and bearing failure modes
FS_e	factor of safety against eccentricity failure mode
DL	distributed dead load surcharge
g	acceleration due to gravity
$g(.)$	limit state function
H	height of geosynthetic reinforced soil wall
k_h	horizontal seismic acceleration coefficient
L	length of the geosynthetic reinforcement
LL	live load surcharge
N_c,N_q,N_γ	bearing capacity factors
P_a	active earth pressure due to backfill soil
P_{ae}	seismic active earth thrust
P_q	active earth pressure due to surcharge load
ΔP_{ae}	seismic component of active earth pressure
K_{ae}	seismic active earth pressure coefficient
q	surcharge load acting on the backfill soil
q_u	ultimate bearing capacity of a shallow foundation
Q	surcharge coefficient
u_i	variables in standard normal space
$X=\{x_i\}_{i=1}^{n}$	vector of random variables representing uncertain quantities
$U=\{u_k\}_{k=1}^{n}$	vector of standard random variables representing uncertain quantities
u^*	most probable point of failure (MPP)
x_i^*	design variable corresponding to target reliability index.
W_{ABFE}	weight of the reinforced soil block '*ABFE*'
W_{AGIE}	weight of the reinforced soil block '*AGIE*'
$\sum F_r$	sum of the horizontal resisting forces
$\sum F_d$	sum of the horizontal driving forces
$\Phi(.)$	the standard normal cumulative distribution
β_t	target reliability index
β_{sli}, β_b	reliability indices against sliding and bearing failure modes
β_e	reliability indices against eccentricity failure mode
COV	coefficient of variation
γ	unit weight of the reinforced backfill soil
γ_b	unit weight of the foundation soil
μ_i	mean of random variable
μ_i^N	equivalent mean of non normal random variable
σ_i	standard deviation of random variable
σ_i^N	equivalent standard deviation of non normal random variable
η_i	load factor
Ψ_i	resistance factor
ϕ	friction angle of the reinforced backfill soil
ϕ_b	friction angle of the soil below the base slab of the retaining wall
δ	interface wedge friction angle between reinforced and retained backfill
δ_b	interface friction angle between wall base and foundation soil
σ_v	vertical stress at the base and
θ_w	angle of slope with vertical.

FHWA [11] reported that the reinforced soil walls must be designed to avoid external modes of failure, viz. sliding failure on its base, overturning failure (or in terms of eccentricity failure of the resultant force striking the footing base) and bearing capacity failure of the foundation soil. American Association of State Highway and Transportation Officials, AASHTO [12] recommended that for static loading, the minimum factors of safety in relation to sliding and overturning modes are 1.5 and 2.0, respectively, and eccentricity of the resultant force should be lesser than one sixth of the width of wall. Further, the minimum factor of safety against bearing capacity failure mode should vary between 2.0 and 2.5. Under earthquake loading, FHWA [11] requires a minimum factor of safety of 1.0 for the design of walls. Currently used design manuals for the design of reinforced soil walls rely primarily on the traditional allowable stress design (ASD) format in which the safety factors are prescribed deterministically. These deterministic safety factors are based on several years of experience and supporting observations from the test data (Choi [13]).

AASHTO [12] has moved away from ASD and accompanying factors of safety for geotechnical design to load and resistance factor design (LRFD). LRFD has the advantage over conventional ASD, in that it accounts for the variability in both resistance and load, as well as provides the same consistent probability of failure for the structure. The first objective of this paper is to evaluate the load and resistance factors for the seismic design of reinforced soil walls against external failure modes with the rigorous probability-based framework of the LRFD approach. The designation LRFD reflects the concept of factoring both loads and resistance. This type of factoring differs from the ASD specification, where only the resistance is divided by a factor of safety (to obtain allowable stress). The LRFD approach was devised to offer the designer greater flexibility, more rationality, and possible overall economy. The format of using resistance factors and multiple load factors is not new, as several such design codes are in effect (AASHTO [12]). In this paper, the use of a probabilistic mathematical model in the development of the load and resistance factors, which made it possible to give proper weight to the accuracy with which the various loads and resistances can be determined.

The partial factors are dependent on the degree of uncertainty and influence of the relevant quantities, and on the desired level of safety. The magnitude of the load and resistance factors is established using probabilistic calculations. A design code developed using LRFD concept provides risk consistency, is likely to result in more economical designs. The reference manual by FHWA [11] reported LRFD approach (refer to Chapter 14) for the mechanically stabilized earth walls, and presented a first step toward developing load and resistance factors, addressing static loading. For the design of reinforced soil walls, the current FHWA [11] recommends the resistance factors in bearing capacity mode range from 0.35 to 0.60 depending on the design method, and for base sliding mode it should be 1.0. However, the existing resistance factors are recommended for static loading and based on the variability associated with the properties of the backfill that were collected from sites that do not necessarily reflect the variability of local backfill soils or design practice. Therefore, the resistance factors recommended by the existing FHWA [11] code need to be verified before being applied to local backfill condition.

In the recent years, Allen et al. [14], Bathurst et al. [15] and Kulhawy and Phoon [16] described methodologies for LRFD for geotechnical and structural design. Basha and Babu [17] reported the load and resistance factor design (LRFD) approach for the reliability-based seismic design of bridge abutments using pseudo-static limit equilibrium method, considering overturning