MSE walls design in seismic regions

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Abstract. Reinforced soil walls perform relatively well under seismic action due to their flexibility. The current design practices consider the seismic action either by an analytical approach (Mononobe-Okabe formula) or by a pseudostatic analysis (geotechnical software). In both cases the seismic action is considered as a constant force acting in the horizontal direction outwards of the MSE wall. A vertical seismic force component may be added, which is generally a fraction of the horizontal one. Besides the simplified approaches, the seismic load can be considered in a more complex way by using accelerograms in FEM software. This method requires seismic records of the region as well as detailed geotechnical parameters for the foundation and backfill. The above mentioned dynamic approaches are discussed in the article along with their advantages and limitations. Some seismic recommendations from design codes are also included. Lastly, it is explained why the choice of the dynamic analysis method depends on the complexity of the situation.

1 Introduction

Reinforced soil walls are becoming increasingly popular due to their ease in construction, good appearance, and relatively low carbon footprint. It has been proven that the compacted soil within these structures has excellent damping capabilities (Kramer, 1996). Consequently, MSE walls tend to be quite resilient when subjected to seismic events. On the other hand, due to their heterogeneity, certain difficulties arise when attempting to predict the effects of an earthquake on a MSE wall. The existing design methodologies typically incorporate seismic effects through either analytical approaches such as the Mononobe-Okabe formula or pseudostatic analyses using geotechnical software (AASHTO, 2012; Bowles, 1995; EN1998-5, 2004). In these approaches, seismic action is generally considered as a constant horizontal force exerted outward from the Mechanically Stabilized Earth (MSE) wall. Occasionally, a vertical seismic force component is included as a fraction of the horizontal force.

2 MSE walls design

Mechanically Stabilized Earth walls are designed to satisfy several controls such as external, internal, and compound stability. The external stability is similar to other retaining wall types with checks in i) foundation base pressure, ii) base sliding, iii) overturning and iv) deep seated

global stability. The internal stability includes the choice and design of the reinforcements/facing panels so that the following are within acceptable limits: i) the peak tension in the reinforcements, ii) the pullout capacity of the reinforcements, iii) sliding between the reinforcements and iv) facing elements stability. Lastly the compound stability refers to the failure modes that combine both internal and external stabilities. This type of control consists of finding potential failure surfaces that pass through the reinforced soil mass and simultaneously extend in the surrounding areas. For a compound failure to happen it is required that one (or more) reinforcements fail in tension or pullout.

The seismic action is considered as a special load that applies on the MSE wall. Earthquakes are characterized by vibrations of the earth that travel in the form of waves (primary, shear, Rayleigh, love). Since it is a dynamic load, it has not been easy to consider its effects in the design of an earth retaining wall. The main seismic design approaches are summarized below.

2.1 Analytical seismic design (Mononobe-Okabe formula)

One of the most widely used equations for seismic design of earth retaining structures is the Mononobe – Okabe method (Mononobe, 1929; Okabe, 1926) of calculating the coefficient of dynamic earth pressure K_{ae} (active coefficient) and K_{pe} (passive coefficient) shown in Equation 1.

$$\begin{Bmatrix} K_{ae} \\ K_{pe} \end{Bmatrix} = \frac{\sin^2(\alpha_i \pm \theta \mp \phi)}{\cos\theta \sin^2\alpha_i \sin(\alpha_i \pm \theta \pm \delta)\left[1 \pm \sqrt{\frac{\sin(\phi+\delta)\sin(\phi \mp \beta_i - \theta)}{\sin(\alpha_i \pm \theta \pm \delta)\sin(\alpha_i - \beta_i)}}\right]^2} \quad (1)$$

$$\tan^{-1}\theta = \frac{F_h}{F_v} = \frac{k_h}{1 \pm k_v} \quad (2)$$

Where :

- α : the inclination of the back face of the wall
- θ : the seismic force angle as per equation 2
- φ, δ : soil friction angle and soil – wall friction
- kh, kv : horizontal and vertical seismic coefficients

Initially obtained as an extension of the Coulomb theory of earth pressure, this method combines the wall geometry parameters, friction properties and seismic coefficients (Coulomb, 1776). The Mononobe – Okabe approach is based on several assumptions such as: the retaining wall is rigid, the soil behind the wall is cohesionless and the seismic action is considered as constant. All these assumptions may lead to inaccurate evaluation of the seismic force that acts on the MSE wall. However, due to its simplicity it is recommended in design normative (AASHTO, 2012; EN1998-5, 2004) and widely used by engineers.

2.2 Analysis using engineering software

Geotechnical engineers have two main options for calculating the effect of an earthquake using a software: limit equilibrium and finite elements FEM (or finite differences FDM) software. These two types of software are quite different between them, although in some cases their results are comparable.

The limit equilibrium software evaluate the safety coefficient of a MSE wall or slope with

regard to a predefined failure plane that is often circular. Depending on the position where the failure plane is passing, it is evaluated the internal/external or compound stability. The resisting mechanism at the failure plane consists of local friction and cohesion for the soil and tensile/pullout strength of the eventual reinforcements. The seismic action is applied as a pseudostatic force that has a specific value and direction. This type of software just calculates the forces equilibrium and takes no account of elements deformability and time dependency of dynamic loads.

The FEM/FDM software are more complex than limit equilibrium ones and contain plenty of material models for soil and reinforcements. They include the deformability of the elements and dynamic loads (in explicit analysis). The model is analyzed to find the effect of the loads on the system, but a failure plane is not necessarily present. The seismic load may be represented as a pseudostatic force, but also as a variable motion of the foundation.

It is quite common for engineers to use the pseudostatic force approach for representing the seismic action on the model. This is mainly due to the simplicity of this modeling option and because it is available in most of the software.

2.3 Discussion on seismic analysis methods

Analytical calculations are still widely used for the seismic design of MSE walls. Both Eurocode and AASHTO have sections dedicated to this. The external stability in EN1995 is evaluated using the dynamic pressure that the soil at the back of the wall exerts on it, while in AASHTO an additional inertial force of the reinforced soil mass is included (Figure 1).

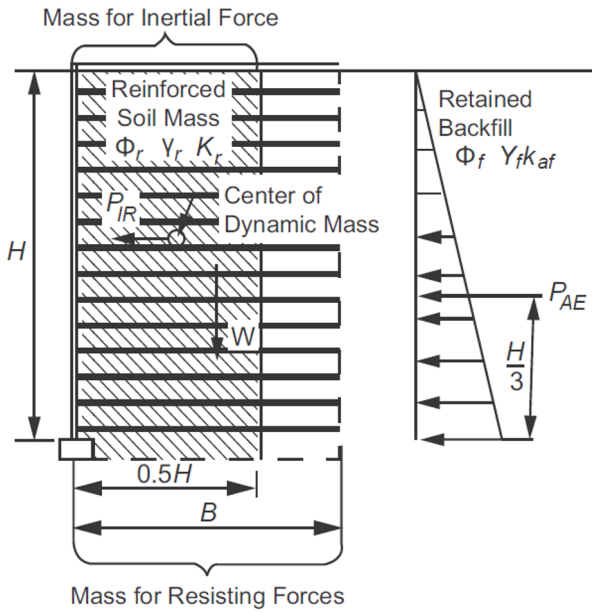

Figure 1: Scheme of dynamic loads on a MSE wall (AASHTO, 2012)

When verifying the external stability of the wall using analytic formulas, one considers the dynamic pressure of the soil behind the MSE wall and also a part of the inertial force acting in wall itself. For the internal stability design, only the inertia of the active wedge behind the facing of the wall is used in the calculation of the dynamic force on the reinforcements. The shape of the wedge depends on whether the reinforcement is geosynthetic or steel.

The pseudostatic representation of the seismic action in different software is typically done by applying the horizontal acceleration in all the model. This seems to be more unfavorable than the analytical approach, which reduces the inertia force in the MSE wall area.

The key factor in the pseudostatic analysis is the horizontal acceleration coefficient "a_g" (usually taken equal to PGA – peak ground acceleration), which is multiplied with the soil factor "S" and divided by a reduction factor of two for walls that can accept displacement (AASHTO, 2012; EN1998-5, 2004). The reduction factor aims to account for the differences of the pseudostatic analysis to the real seismic motion, for example: soil damping, direction change, amplitude, and frequency variation. In other words, applying the PGA as a pseudostatic force would be too conservative since it only happens for a very short time in reality. Although it is widely accepted, the pseudostatic force method remains a simplification and may give unrealistic results especially for high seismicity areas.

The most advanced seismic calculation is currently done using complex models and applying on them seismic accelerograms in an explicit time history analysis. In this type of calculation, one needs to define special behaviors for soil and reinforcements that take into account the dynamic nature of the load. For implementing such a model one needs to consider soil damping. The latter can be quite challenging since several options exist and they all vary for different soils. So, damping requires a certain level of expertise for choosing the one that better represents the backfill of the wall without greatly increasing the computation time.

3 Conclusions

Seismic analysis of MSE walls can be performed either by analytical or numerical methods. Both contain assumptions and simplifications in the input and output data. Analytical methods are widely accepted and recommended in different normative. Numerical approaches with geotechnical software aim to give more details with regard to output and seem to be more conservative than analytical ones when pseudostatic analysis is used.

The benefit of FEM/FDM software is that they give an estimation of the behavior of the structure by predicting its stresses and deformation in any location. However, the uncertainty of the input parameters and material behavior is always present in dynamic calculations.

For most cases the pseudostatic analysis would be a convenient method as long as it does not lead to big changes compared to the static design of a MSE wall. In highly seismic areas it might be worth to investigate the application of complex models using time history analysis. It is possible that the soil damping characteristics would lead to a more optimized design

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