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Active static and seismic earth pressure for c–φ soils

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Abstract

Rankine classic earth pressure solution has been expanded to predict the seismic active earth pressure behind rigid walls supporting c–φ backfill considering both wall inclination and backfill slope. The proposed formulation is based on Rankine's conjugate stress concept, without employing any additional assumptions. The developed expressions can be used for the static and pseudo-static seismic analyses of c–φ backfill. The results based on the proposed formulations are found to be identical to those computed with the Mononobe–Okabe method for cohesionless soils, provided the same wall friction angle is employed. For c–φ soils, the formulation yields comparable results to available solutions for cases where a comparison is feasible. Design charts are presented for calculating the net active horizontal thrust behind a rigid wall for a variety of horizontal pseudo-static accelerations, values of cohesion, soil internal friction angles, wall inclinations, and backfill slope combinations. The effects of the vertical pseudo-static acceleration on the active earth pressure and the depth of tension cracks have also been explored. In addition, examples are provided to illustrate the application of the proposed method.

Keywords: Mononabe–Okabe method; Rankine; Retaining wall; Seismic; Limit state analysis

1. Introduction

The estimation of seismic active earth pressure on retaining walls from backfill soils is an important problem in earthquake engineering. Pioneering works on seismic earth pressure on a rigid retaining wall have been reported by Okabe (1924) and Mononobe and Matsuo (1929, 1932). Their analyses have provided a popular solution to the problem of cohesionless soils. The Mononobe–Okabe (M–O) method is a pseudo-static approach, which incorporates seismic accelerations in the form of inertial forces into Coulomb's 1776 limit equilibrium analysis (Heyman, 1997). While the original M–O solution did not account for cohesion, several authors have extended the M–O solution to account for c–φ soils. For example, Saran and Prakash (1968) and Saran and Gupta (2003) proposed a solution for seismic earth pressure on a retaining wall supporting c–φ soils, in which the contributions of soil weight and cohesion are optimized separately, in some cases leading to two distinct failure planes. Shukla et al. (2009) developed an expression for the total seismic active force on a retaining wall supporting c–φ backfill based on the Coulomb sliding wedge concept, disregarding the soil–wall friction component. In all Coulomb type of solutions, only force equilibrium is used; and therefore, the distribution of the lateral thrust is not determined. On the other hand, Rankine's (1857) active earth pressure is a stress field-based solution, which does not require specifying failure kinematics (Huntington, 1957). The original Rankine solution considered static lateral earth pressure against

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a vertical rigid wall supporting cohesionless backfill with a ground surface unlimited in lateral extent and depth. Chu (1991) extended Rankine's method to account for wall inclination, and Mazindrani and Ganjali (1997) presented a similar solution for cohesive backfill under static conditions. Limitations of stress-based solutions, as well as a discussion on the general limitations of Coulomb-type solutions can be found in Mylonakis et al. (2007).

In addition to Coulomb and Rankine's earth pressure theory, other theoretical solutions have been developed to compute lateral earth pressure. Caquot and Kerisel (1948) developed tables of earth pressure coefficients based on the logarithmic spiral failure surface. Sokolovskii (1965) developed a characteristic method to compute lateral earth pressure based on a finite-difference solution. Habibagahi and Ghahramani (1979) developed a solution for lateral earth pressure coefficients based on the zero extension line theory. Notwithstanding the significance of these contributions, none of the aforementioned methods can be used for c–φ backfill under seismic conditions. Richards and Shi (1994) presented a plasticity-based solution to calculate seismic lateral earth pressure limited to vertical walls retaining horizontal c–φ backfill. Due to the complexity of the soil–wall interaction, numerical techniques have recently been adopted to compute the seismic earth pressure against a retaining wall (Al-Homoud and Whitman, 1994; Gazetas et al., 2004; Psarropoulos et al., 2005; Madabhushi and Zeng, 2007; Tiznado and Rodriguez-Roa, 2011). However, numerical modeling is generally costly, time consuming and difficult to implement.

In practice, when computing earth pressure against retaining walls, it is often assumed that the backfill is cohesionless. However, most natural deposits have some fines content that exhibits some degree of cohesion (Sitar et al., 2012). Anderson et al. (2008) found that the contribution of cohesion to a reduction in seismic earth pressure on retaining walls could be in the order of approximately 50%. Lew et al. (2010a, 2010b) compared the seismic performance of various retaining structures in recent earthquakes and reached a similar conclusion. Therefore, it is worthwhile to consider the cohesion in backfill for retaining structure problems. As pointed out by Sitar et al. (2012), "*the costs of an overconservative design can be just as much of a problem as the cost of a future failure*". Other factors, including the generation of negative pore air pressure in backfills during earthquakes (Koseki et al., 2010) and the outward movement of a retaining wall under large seismic loads (Watanabe et al., 2011), may also reduce the seismic active earth pressure.

In this paper, Rankine's conjugate stress approach for pseudo-static active earth pressure behind inclined rigid walls supporting sloped backfill, proposed by Iskander et al. (2012), has been generalized for cohesive backfill. The validity of the solution is demonstrated through a comparison with the available solutions to the problem.

2. Analytical formulation

The original Rankine active earth pressure solution assumes that the soil behind a retaining wall follows the movement of the wall, and the whole soil mass is subjected to uniform lateral extension. This implies that a uniform stress field exists and that the stress field of the soil behind the wall will be equal to that in the free field. This assumption is generally not true, since the stress in the near field behind the wall is different from that in the free field due to the difference in the movement between the wall and the free field (Richards et al., 1999) and the effects of soil arching (Paik and Salgado, 2003). However, following Rankine's original assumptions, we assume in this paper that the stress field adjacent to the wall is the same as that in the free field, disregarding the errors associated with such an assumption.

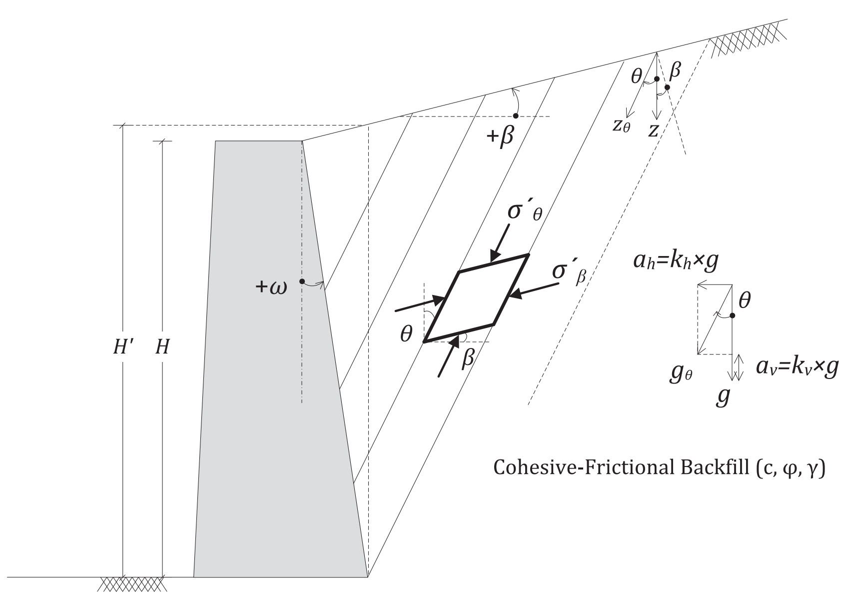

Fig. 1. Problem geometry and conjugate stress state in soil element behind backfill.