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Technical Paper

Theoretical analysis of earth pressure against rigid retaining walls under translation mode

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Abstract

The soil mass behind a retaining wall gradually yields and separates from the stationary soil mass with the complex shape of the slip surface depending on the mode of wall movement and roughness of the wall surface. In this study, the problem of a rigid retaining wall with a uniform surcharge acting along the horizontal backfill under active translation mode is investigated in a two-dimensional system of equilibrium. Exact stress solutions based on Janssen's approach are generalized in rectangular coordinates and are validated with boundary conditions on the retaining wall and at the Coulomb slip line behind the wall. Because the yield condition is not used in Janssen's approach, the proposed solution is a merely static stress solution, not statically admissible solution. New equations are developed to estimate the magnitude and distribution of vertical, horizontal and shear stresses in the failure zone behind a retaining wall. The proposed analysis indicates the arching effect behind the retaining wall because the maximum stresses do not appeared at the toe; but at some distance away from the toe of the retaining wall. The results of the proposed formulations are compared with both full-scale and laboratory-scale experimental data as well as the existing formulations. The proposed analysis provides comparable approximations for horizontal active stress distribution, the magnitude and the application height of the horizontal active force at the wall.

Keywords: Retaining walls; Soil/structure interaction; Arching effect; Earth pressure; Stress analysis; Failure

1. Introduction

Conventionally, the active earth pressure against rigid retaining walls has been calculated by using Coulomb (1776) or Rankine (1857) formulation with a consequence of linear distribution of active earth pressure against the wall. However, many experimental results (Tsagareli, 1965; Sherif and Fang, 1984; Fang and Ishibashi, 1986; Chang, 1997; Take and Valsangkar, 2001; O'Neal and Hagerty, 2011) show that the distribution of active earth pressure on a wall is non-linear for rough walls. According to Iskander et al. (2013), this non-linearity depends on the mode of wall movement and soil-wall friction angle.

The arching theory is attributed to Janssen (1895) with his observation of non-hydrostatic pressure in granular material stored in silos (Sperl, 2006). A differential equation for pressures in silos was formulated using force equilibrium along the direction of gravity under the assumption that the ratio of horizontal-to-vertical stress is constant. Janssen's stress solution in the form of an exponential function with depth provides the theoretical basis for arching effects in silos. More details relating to methods originating from the Janssen's

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Nomenclature

The following symbols are used in this study:

x	horizontal distance measuring from the toe of the wall in a rectangular coordinate system
z	vertical distance measuring the from toe of the wall in a rectangular coordinate system
σ_1, σ_2, σ_3	major, intermediate and minor principal stresses
σ_x	horizontal stress
σ_z	vertical stress
τ_{xz}	shear stress
σ_{xw}	horizontal stress at the wall
σ_{zw}	vertical stress at the wall
τ_w	shear stress at the wall
α	angle between the slip surface and the wall measured from the vertical ($\alpha = \pi/4 - \phi/2$)
ρ	bulk density of the retained soil
γ	unit weight of the retained soil
ϕ	internal friction angle of the retained soil
δ	interface friction angle between the wall and the retained soil
μ_w	coefficient of wall friction ($\mu_w = \tan\delta$)
H	height of the retained soil
h	height measured from the top of the wall
h_a	height of application of the horizontal active force measured from the top of the wall
K_w	Krynine (1945)'s horizontal-to-vertical active stress ratio at the wall
K_a	Rankine (1857)'s active earth pressure coefficient
M	moment of the horizontal active stress about the wall base
n	constant number defined by $n = \mu_w K_w / \tan\alpha$
P_a	total active force on the wall
P_{ah}	horizontal active force normal to the wall
Q	uniform surcharge on the top surface of the retained soil
T	shearing force on the wall

concept can be found in Drescher (1991). Efforts have been made to extend Janssen's original one-dimensional description to two-dimensional descriptions in both rectangular and cylindrical coordinate systems using the additional assumption of uniform pressure across the horizontal plane which is equivalent to linear shear stress reduction from the wall (Jáky, 1948; Millet et al., 2006; Rahmoun et al., 2008; Rahmoun et al., 2009; Pipatpongsa and Heng, 2010).

Terzaghi (1943) found that the maximum earth pressure does not appear at the lower end of the wall but is located at a certain higher level. He used the term "arching in soils" and explained that soil arching is the ability of soil material to transfer shear stresses to a more stable portion. The concept of soil arching was experimentally realized using a trap door and a retaining wall. When a part of the support yielded, the soil on that part would tend to move toward the yielding support but the relative movement is resisted by the frictional resistance; hence, shear stress is transferred onto adjacent stationary parts.

Investigations of the silo effect have been extended to conical and wedge-shaped hoppers by Walker (1966) and Walters (1973). The width of the differential flat element is not constant like that of a silo problem but varies with depth. Later, Walters refined Walker's stress solution by considering the inclined shear stress acting along the edge of the differential flat element. The derived stress solutions in terms of a power function with depth provide the theoretical basis for arching effects in hoppers.

Later, many authors also described earth pressure distributions in terms of arching action (action (Marston and Anderson, 1913; Getzler et al., 1968; Wang and Yen, 1974). Handy and Spangler (2007) initially developed equations based on Janssen's arching theory to estimate the distribution of active horizontal stress against rigid retaining walls. The assumption of a wedge-shaped failure zone was employed in addition to the one-dimensional basic formulation of a silo. Later, several other researchers also attempted to apply the arching effect in the estimation of active earth pressures against rigid retaining walls (Handy, 1985; Harrop-Williams, 1989a, 1989b; Wang, 2000; Paik and Salgado, 2003; Goel and Patra, 2008; Nadukuru and Michalowski, 2012). Some of those researchers combined the basic formulation of stress in hoppers with a wedge-shaped failure zone assumption in retaining walls under horizontal translation mode and formulated a one-dimensional stress solution in the form of a power function with depth (Harrop-Williams, 1989b; Wang, 2000; Paik and Salgado, 2003; Goel and Patra, 2008). Nadukuru and Michalowski (2012) demonstrated arching in distribution of active load on retaining walls using discrete element method and differential slice method.

So far, all of those existing formulations have been investigated in a one-dimensional system of equilibrium by assuming a differential flat element between the wall and the Coulomb slip line behind the wall. Though these arching-based solutions were formulated in the bounds of the Coulomb wedge for a case of a smooth vertical wall and horizontal backfill, they are different from the classical Coulomb solution because not only the total force but the stress distribution along the wall are also obtained. The simplification of the formulations by averaging vertical pressure helps obtain the stress distribution only along the wall, but the stress distribution in the failure zone between the wall and the slip line still remains unclear.

Active earth pressure distribution under horizontal translation, rotation about the top, and rotation about the base are typical modes of movement for rigid retaining walls conventionally considered (Terzaghi, 1943). Fang and Ishibashi (1986) experimentally showed that, though the active wall displacement necessary to mobilize the active state at each depth of the wall is independent of types of wall movement, the pattern of horizontal pressure distribution along the wall