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Research Paper

Three-dimensional active earth pressure coefficients by upper bound numerical limit analysis

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A B S T R A C T

A 3D numerical implementation of the limit analysis upper bound theorem is used to determine active horizontal earth pressure coefficients. Results of the ratio between the 3D and 2D horizontal active earth pressure coefficients for both soil weight and surcharge are shown and found to be almost independent of the soil-to-wall friction ratio, as is the case with passive earth pressure coefficients. A simple equation is proposed for calculating this active earth pressure ratio and it is compared with previously published results.

1. Introduction

Determination of active and passive earth pressures is a classical soil mechanics problem which continues to be addressed in recent studies focusing different issues, such as seismic actions [1] and seepage effects [2], using different techniques, such as elastoplastic numerical methods [3], limit analysis [4] and limit equilibrium [5]. All these studies were performed in plain strain conditions; cases of axi-symmetric conditions could also be found in the literature [6,7] and recently some results of 3D numerical calculations were published [8].

The problem of the determination of three-dimensional active earth pressures has been addressed in the past by Huder [9], using the two-dimensional arching theory of Janssen [10] and Terzaghi [11] and by Walz and Prager [12], extending Terzaghi's theorie for three-dimensional cases. Due to arching effects, three-dimensional active earth pressures are smaller, which can be relevant in the design of certain narrow retaining structures and trenches for diaphragm walls.

The authors made a contribution to the problem of three-dimensional passive earth pressure coefficients [13], using sublim3D [14], a finite element limit analysis program which uses a finite element mixed formulation that implements the upper-bound theorem. In that work, values for the horizontal passive earth-pressure coefficients were presented. It was found that the ratio between 3D and 2D horizontal passive earth pressure coefficients does not depend significantly on the soil-to-wall friction ratio. An equation was proposed to allow the simple determination of that ratio as a function of ϕ' and of the width-to-height ratio. More recently, tom Worden and Achmus [8] found the same independence from the soil-to-wall friction ratio, for the case of the active earth pressure ratio.

In the present paper the sublim3D finite element program is applied to the determination of 3D active earth-pressure coefficients.

The sublim3D software always provides strict upper bound estimates of the plastic collapse load. This code scales the mechanism by setting the work rate of the external forces affected by the load parameter equal to one and performs the minimization of the difference between the plastically dissipated work rate and the work rate of the fixed external forces using the alternating direction method of multipliers [15]. In addition, the program uses distributed parallel computing techniques which allow large-scale problems to be solved. The sublim3D software was first developed using linear approximations for the velocity field [14] and later using quadratic approximations [16].

2. Definition of the problem

The geometry of the analyzed problem is represented schematically in Fig. 1. The wall is vertical and rigid with width b and height h. The soil free surface is assumed to be horizontal.

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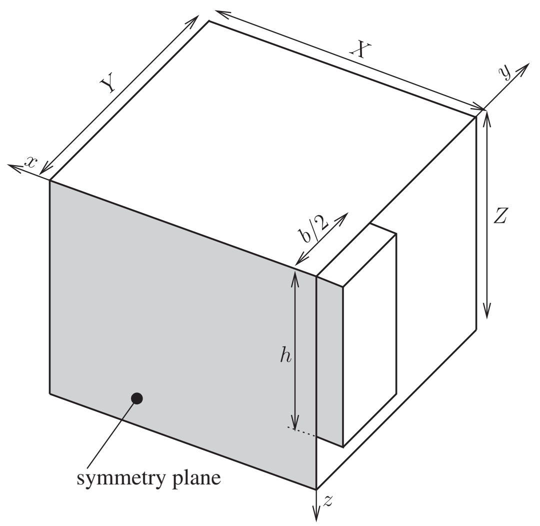

Fig. 1. Definition of the geometry of the problem.

A Mohr–Coulomb yield criterion with cohesion equal to zero is assumed for the soil strength. Two active earth pressure coefficients are determined, $K_{a\gamma}$ and K_{aq}, representing the influence of soil weight and of constant surcharge loading, respectively. For the case of zero surcharge loading, the active force per unit width $I_{a\gamma}/b$ can be written as:

$$\frac{I_{a\gamma}}{b} = \frac{1}{2} K_{a\gamma} \gamma h^2 \quad (1)$$

where γ is the soil unit weight and the other symbols have the meaning described previously. For the case of zero soil weight and surcharge loading q, the active force per unit width I_{aq}/b can be written as:

$$\frac{I_{aq}}{b} = K_{aq} q h \quad (2)$$

As an approximation, it can be assumed that when $\gamma \neq 0$ and $q \neq 0$ the active force per unit width I_a/b can be determined as the sum of Eqs. (1) and (2):

$$\frac{I_a}{b} = \frac{1}{2} K_{a\gamma} \gamma h^2 + K_{aq} q h \quad (3)$$

Table 1
Values of $K_{a\gamma h}$ obtained for different $b/h, \phi'$ and δ/ϕ'.

b/h	ϕ' (°)	$K_{a\gamma h}$				
		$\delta/\phi' = 0$	1/3	1/2	2/3	1
0.25	15	0.3663	0.3391	0.3285	0.3194	0.3050
	20	0.2674	0.2430	0.2335	0.2253	0.2120
	25	0.1961	0.1758	0.1679	0.1610	0.1495
	30	0.1454	0.1302	0.1236	0.1178	0.1080
	35	0.1051	0.0966	0.0913	0.0866	0.0782
	40	0.0730	0.0726	0.0684	0.0646	0.0576
	45	0.0607	0.0533	0.0502	0.0473	0.0341
0.5	15	0.4660	0.4341	0.4215	0.4106	0.3934
	20	0.3634	0.3332	0.3212	0.3108	0.2941
	25	0.2824	0.2561	0.2454	0.2361	0.2207
	30	0.2179	0.1970	0.1878	0.1798	0.1660
	35	0.1637	0.1507	0.1431	0.1363	0.1242
	40	0.1162	0.1152	0.1091	0.1035	0.0931
	45	0.0976	0.0866	0.0819	0.0775	0.0685
1	15	0.5248	0.4917	0.4785	0.4671	0.4496
	20	0.4233	0.3909	0.3781	0.3669	0.3494
	25	0.3401	0.3106	0.2988	0.2885	0.2718
	30	0.2715	0.2464	0.2360	0.2267	0.2114
	35	0.2141	0.1946	0.1856	0.1776	0.1638
	40	0.1643	0.1526	0.1452	0.1383	0.1260
	45	0.1322	0.1184	0.1125	0.1069	0.0961
2	15	0.5600	0.5225	0.5091	0.4976	0.4801
	20	0.4557	0.4226	0.4093	0.3978	0.3799
	25	0.3718	0.3466	0.3288	0.3265	0.3007
	30	0.3005	0.2741	0.2631	0.2534	0.2372
	35	0.2406	0.2192	0.2098	0.2011	0.1864
	40	0.1881	0.1737	0.1658	0.1585	0.1453
	45	0.1508	0.1359	0.1295	0.1235	0.1119
5	15	0.5750	0.5416	0.5282	0.5166	0.4990
	20	0.4755	0.4421	0.4287	0.4171	0.3989
	25	0.3907	0.3597	0.3472	0.3362	0.3185
	30	0.3195	0.2918	0.2805	0.2705	0.2538
	35	0.2577	0.2346	0.2248	0.2160	0.2008
	40	0.2047	0.1868	0.1786	0.1710	0.1574
	45	0.1619	0.1464	0.1398	0.1335	0.1217
∞ (2D)	15	0.5884	0.5547	0.5413	0.5296	0.5122
	20	0.4895	0.4557	0.4422	0.4305	0.4123
	25	0.4048	0.3731	0.3604	0.3492	0.3313
	30	0.3318	0.3037	0.2922	0.2820	0.2652
	35	0.2690	0.2450	0.2351	0.2260	0.2106
	40	0.2149	0.1952	0.1869	0.1792	0.1654
	45	0.1682	0.1529	0.1461	0.1397	0.1277