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Seismic earth pressure including soil cohesion

Prise en compte de la cohésion dans la poussée séismique

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ABSTRACT
Normally, seismic earth pressures against retaining structures are computed assuming zero cohesion in the retained soil. This criteria is supported on seismic strains in the retained soil which can destroy the soil cohesion, ending with a pure frictional material. However, it is possible to establish a strain dependent variation for the soil cohesion and the soil angle of friction as well as a relationship between the horizontal seismic displacement of the retaining structure and the strain of the retained soil. By combining these parameters it is possible to define the cohesion to be used in the design. This methodology is illustrated for a cantilever retaining wall with a silty sand from volcanic origin (pumice) used as fill material.

RÉSUMÉ
Normalement, les poussées induites par séismes contre les structures de contention sont calculées en négligeant la cohésion du sol retenu. Ce critère s'appui sur la supposition que les déformations induites dans le sol retenu par le séisme détruisent la cohésion, le sol se transformant en un matériau purement pulvérulent. Cependant, il est possible d'établir une relation entre l'évolution de la cohésion ainsi que de l'angle de frottement avec la déformation, et une relation entre le déplacement séismique horizontal de la structure de contention et les déformations du sol retenu. En combinant ces paramètres, une cohésion peut être prise en compte pour le dimensionnement. Cette méthodologie est appliquée à un mur de contention du type cantiliver avec un sable limoneux d'origine volcanique (pumice) utilisé comme matériau de remblai.

1 INTRODUCTION

Determination of static thrusts on earth retaining structures including soil cohesion has been resolved decades ago. For seismic thrusts, the first practical solution corresponds to the Mononobe (1925) and Okabe (1924) expression. This expression is based on the Coulomb's wedge method, incorporating the seismic inertia through an horizontal seismic coefficient, k_h, applied to the weight of the wedge. For such effect, every point on the wedge is submitted to the same seismic coefficient, and the wedge responds like a rigid body. The Mononobe and Okabe expression has the limitation of not introducing soil cohesion, which was later included by Prakash (1981), also employing the Coulomb's wedge method. Based on Prakash's expressions, this work proposes resolving the problem uncoupling the static and seismic thrust in the following manner:

- Determining the resultant static thrust, E_{EC}, including soil cohesion, c, with tension cracks.
- Determining the resultant static plus seismic thrust, E_{ES}, with the Mononoke and Okabe expression, which implicates considering c = 0.
- Determining the resultant static thrust, E_{EO}, by making c=0.
- Determining the seismic thrust component as:

$$E_S = E_{ES} - E_{EO} \qquad (1)$$

In this manner, the resultant of the static plus seismic thrust is obtained as:

$$E_R = E_{EC} + E_S \qquad (2)$$

It is important to point out that the thrust uncoupling is valid if $E_{EC} > 0$, which equates to consuming all soil cohesion in the static thrust component. If the cohesion is such that the critical height of the soil is equal to that of the wall, the uncoupling gives $E_{EC} = 0$ and if it is greater gives $E_{EC} = 0$ and an overvalued seismic component.

The distribution of the static thrust resultant has an hydrostatic or rectangular form, depending on the nature of the retaining element and of its construction system, while the seismic component is normally represented by an inverted triangle, even when recent investigations locate the resultant in the way presented in Fig. 1.

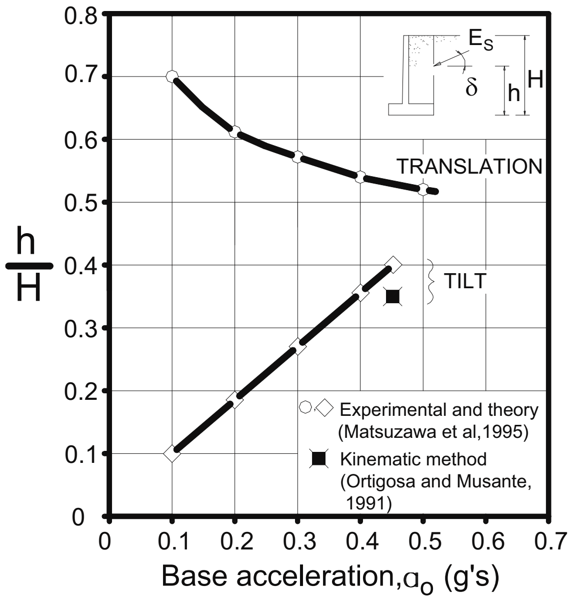

Fig. 1 Location of the seismic component for a cantilever wall

More recently, Richards and Shi (1994) utilize an interaction model between the retaining element and the free field seismic movement of the soil in which they incorporate cohesion. In Fig. 2 it is shown the results obtained by these authors, which are similar to those obtained by the thrust uncoupling as presented earlier, particularly for k_h = 0.10 to 0.20 which is the typical design range established by the Chilean Highway Manual for gravity retaining walls. The comparison presented in Fig. 2 corresponds to a soil with an angle of friction $\phi = 30°$ and a cohesion defined as $c = 0.1 \gamma H$, where γ is the unit weight of the soil and H the height of the wall. As a reference, Fig. 2 includes results for null cohesion.

The methods that incorporate cohesion consider that it remains constant, regardless of the magnitude of seismic displacement of the retaining structure. This condition must be checked incorporating the decrease (degradation) of the soil cohesion with wall deformation, especially in gravity walls that experiment permanent seismic displacements.

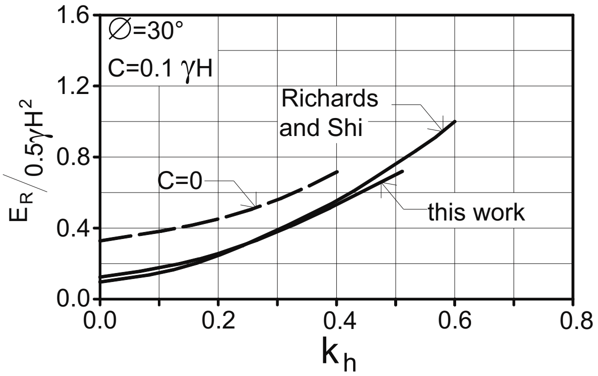

Fig. 2 Normalized total thrust with tension craks

2 VARIATION IN COHESION WITH DEFORMATION.

The mobilization of pair c - ϕ in function of the deformation, ε, that a soil experiments can be obtained with triaxial compression tests and, ideally, with unloading compression triaxial tests, since the latter represent the soil stress path behind the retaining structure with greater fidelity. Normally, professional practice utilizes triaxial compression tests, by which it is possible to define a family of envelops for different deformations, such as those shown on Fig. 3 for the Santiago Gravel. Starting from these envelopes the mobilization c - ϕ - ε is obtained as represented in Fig. 4. A similar process to the one described was applied to compacted samples at 95% of Modified Proctor with a compaction water content $\omega_c = 0.5\ \omega_{opt}$. The samples corresponded to fine sands of volcanic origin, without plasticity and with a percentage of fines between 25% and 40% (pumice). Pumices were tested from six different borrows to be used as fill material behind retaining walls for the construction of freeways in the city of Santiago. Illustrated in Fig. 5 is the band for c - ϕ - ε obtained for the six borrows.

In both Santiago Gravel and the pumice it is observed that cohesion reaches a maximum, c_{max}, which is associated with an angle of friction, ϕ_m, for a well-defined deformation. For greater deformations cohesion decreases while the angle of friction continues increasing.

The uncoupling c - ϕ - ε has been successfully applied in explaining fragile-type failures in slopes and in the interpretation of thrust measurements in earth support systems in the Santiago Gravel (Ortigosa, 1998).

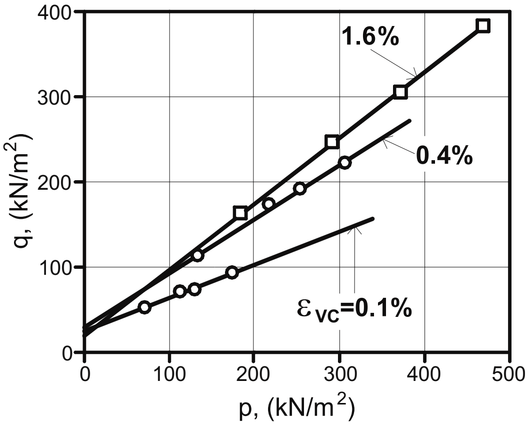

Fig. 3 Envelops for the 1st deposit of the Santiago Gravel from in-situ compression triaxial tests (Kort et al, 1979).

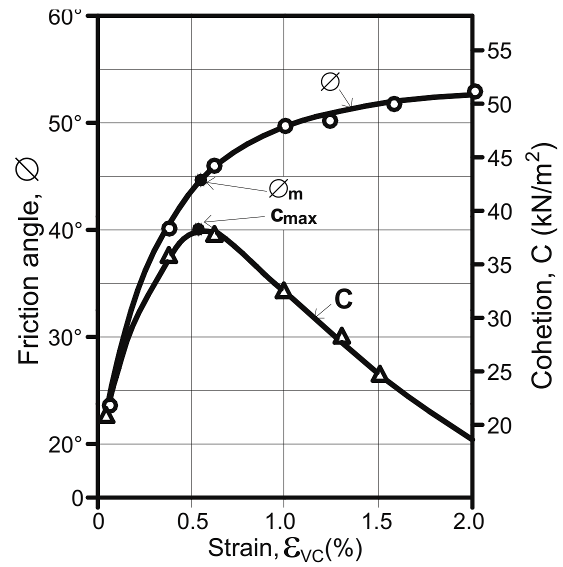

Fig. 4 Curves c-ϕ-ε for the 1st deposit of the Santiago Gravel (Kort et al, 1979).

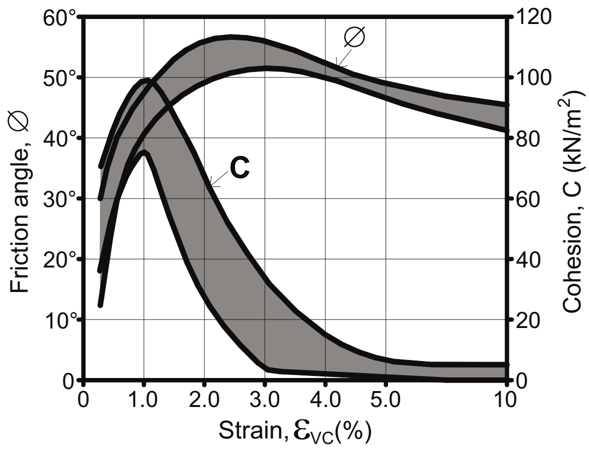

Fig. 5 Curves c-ϕ-ε (compression triaxial test for compacted Pumice at 95% Modified Proctor with $\omega_c = 0.5\omega_{opt}$)

3 APPLICATION IN COMPUTING EARTH PRESSURES.

Soil thrust on a retaining structure depends on the mobilized pair c - ϕ, which in turn is a function of the soil deformation, ε. In order to connect this deformation with the seismic displacement of the retaining structure, Δ_S, which is commonly expressed as a normalized displacement by the height of the wall, Δ_S/H, Fig. 6 represents two approximations. In granular soils the Poisson module, ν, is in the order of 0.30, and for practical effect it can be established:

$$\varepsilon_{vd} = 4 \frac{\Delta_s}{H} \tag{3}$$

in which ε_{vd} is the vertical deformation of the retained soil for a stress path of unloading compression. With the aim of directly utilizing the curves c - ϕ - ε obtained through the classic compression triaxial tests, the corresponding deformation for this type of triaxials, ε_{vc} , can be expressed as:

$$\varepsilon_{vc} = \frac{\varepsilon_{vd}}{F_d} \tag{4}$$

in which F_d typically varies between 0.12 and 0.23 for compacted soils, being able to adopt an average value equal to 0.17. Certainly, the ideal is directly obtaining the relation c - ϕ - ε through unloading compression triaxials tests, thus avoiding to work with an approximate average value.

Combining equations (3) and (4) with F_d = 0.17, it is obtained:

$$\varepsilon_{vc} = 23.5 \frac{\Delta_s}{H} \tag{5}$$

Equation (5) permits the direct utilization of the c - ϕ - ε design curves for compacted pumice shown in Fig. 5. In this way, for a given seismic displacement Δ_S/H the deformation ε_{vc} can be determined through ec.(5). Using this ε_{vc} value in Fig. 5 it is possible to obtain the design pair c - ϕ to determine the soil thrust.

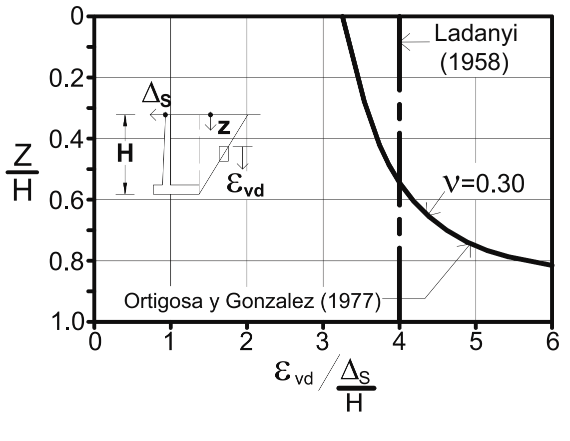

Fig. 6 Soil strain due to the seismic displacement of the retaining wall

4 RESULTS

Represented in Fig. 7 is the variation of the static thrust for pumice, E_{EC}, in function of the normalized seismic displacement of a cantilever retaining wall, while the variation corresponding to the seismic thrust component, E_S, obtained with equation (1) is represented in Fig. 8. It is appreciated that E_{EC} as well as E_S are affected by the magnitude of seismic displacement of the wall.

Of special interest is the thrust obtained with the average pair c = 60 kN/m^2 and ϕ = 51° defined by the maximum deviatoric stress for the six pumice borrows, through which a static thrust E_{EC} = 0 is obtained. Taking into account that this resistant pair is mobilized for a soil deformation, ε_{vc}, around 1.5%, according to ec.(5) the normalized seismic displacement of the wall to generate that deformation must be equal to 0.65 x 10^{-3}, which can be amply surpassed during a severe earthquake. In effect, if the retaining wall is designed with a seismic coefficient equal to 50% of the maximum expected acceleration, according to the procedures established in the Chilean Highway Manual it is possible that a seismic wall displacement of up to 2.5 cm can be generated, which implies Δ_S/H = 3.1 x 10^{-3} to 8.3 x 10^{-3} for walls with a height of 8 and 3 m, respectively. This range of normalized seismic displacements exceeds 5 to 13 times the required displacement to mobilize the pair c - ϕ obtained with the maximum deviatoric stress, generating a static thrust $E_{EC} > 0$. Thus, it can be ratified that the selection of cohesion in determining the soil thrust in seismic conditions must consider its degradation with the seismic displacement of the wall. The employment of a unique cohesion, independent of wall displacement, and obtained with the classical failure envelope associated to the maximum deviatoric stress leads, in the case of the tested pumice, to insecure design thrusts as indicated in Table 1.

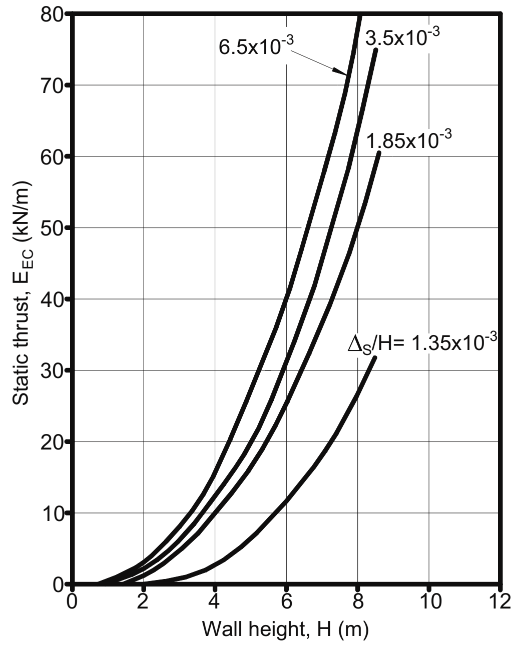

Fig. 7 Static thrust for compacted pumice with γ = 15 kN/m^3

Table 1: Thrusts under seismic conditions for compacted pumice with k_h = 0.15 and Δ_S = 2.5 cm.

Wall height H(m)	Maximum deviatoric			Utilizing c-ϕ-ε		
	E_{EC} (kN/m)	E_S (kN/m)	E_R (kN/m)	E_{EC} (kN/m)	E_S (kN/m)	E_R (kN/ml)
3	0.0	3.7	3.7	8	5	13
4	0.0	6.5	6.5	15	8	23
6	0.0	15	15	33	17	50
8	0.0	26	26	60	31	91

5 COMPARISONS

In order to obtain the reinforced concrete volume, a cantilever wall with height of 10m was selected. In one case a clean sandy gravel with c = 0, ϕ = 40º and γ = 22 kN/m^3 was considered as fill material, while in the other case the fill material was pumice with c = 6 kN/m^2, ϕ = 35º and γ = 15 kN/m^3. Table 2 shows the concrete volume and steel reinforcement per linear meter of wall including looses (3% for steel an 5% for concrete). Total local costs of materials supply are also shown without including placement costs.

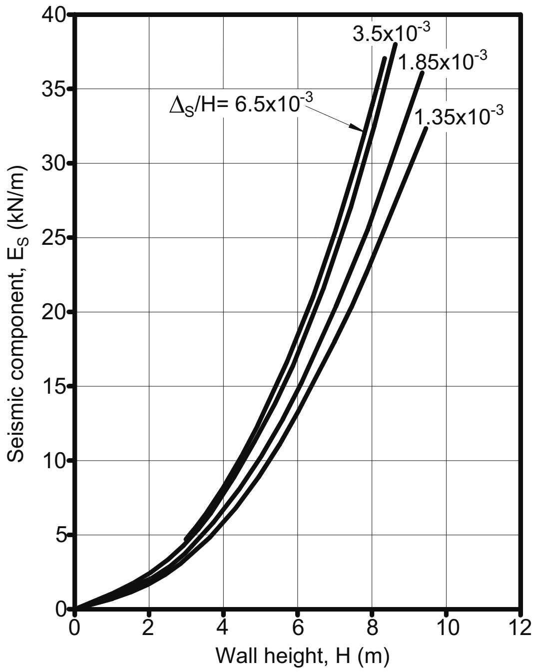

Fig. 8 Seismic thrust component for $k_h = 0.15$ using compacted pumice with $\gamma = 15$ kN/m^3

Table 2: Cost of materials supply

Fill	Concrete Volume m^3/m	Steel reinforcement ton/m	Total cost US dollars/m
Pumice	15.2	1.13	1582
Sandy Gravel	19.4	1.42	2005

Cost difference in materials supply for a wall of 10m in height is US 423 dollars/m, which can be reduced to US 215 dollars/m for an average wall height of 5m. Taking into account a total wall length of about 30 Km for three projects actually under construction, the materials cost supply is reduced in the order of US 6.5 millions.

6 CONCLUSIONS

The uncoupling of pair c - ϕ in function of the soil deformation permits the definition of the cohesion degradation generated by the seismic displacement of an earth retaining structure. For the tested pumice samples, the utilization of a unique cohesion, independent of the wall seismic displacement, and obtained with the maximum deviatoric stress in triaxial tests, leads to underestimating the resulting thrust in seismic conditions. As a consequence, to include cohesion in determining thrusts in seismic conditions, this parameter must be defined taking into account the maximum expected seismic displacement of the retaining structure.

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