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Model behavior of reinforced earth walls

Comportement de modèles réduits de murs en terre armée

On présente les résultats de modèles réduits tridimensionnels de murs en terre armée et leur comparaison avec les méthodes de dimensionnement reposant sur les théories de Rankine et de Coulomb. Les espacements horizontal et vertical entre les armatures ont été les deux paramètres pris en compte dans les modèles.

INTRODUCTION

Since the introduction of the concept of reinforced earth by Vidal (10), there have been many notable contributions toward extending our understanding of the behavior of reinforced earth. These studies have dealt both with the likely principles which govern the mechanism of earth-reinforcement interaction and the potential models which could be used in the design of reinforced earth structures. The study herein is limited to behavior under static conditions.

The basic design of a reinforced earth wall involves the arrangement of a network of metal ties with respect to their lengths and horizontal and vertical spacing for a particular type of backfill material. As it would be expected for relatively shorter ties, beyond a certain height of construction, a wall failure by tie pull-out would be initiated whereas for relatively longer ties the mode of failure would be through tie breakage (4, 6). These two modes of failure have been extensively studied during the last decade by model and in-situ tests at the Laboratoire Central des Ponts et Chaussees (LCPC) (5, 6, 8) and University of California at Los Angeles (UCLA) (2, 3). In UCLA studies the basic model variables were selected as tie length (L) and horizontal spacing of ties (s) while the vertical spacing of ties (x) was kept constant at 1 in. (25.4mm). In this study, model tests basically identical to UCLA models were performed, except that the vertical spacing of ties (x) was selected as the variable parameter while the horizontal spacing of ties (s) was kept constant at 6 in. (152.4mm). Observed model behavior have been examined in line with the currently used design formulations.

MODEL TESTS

The general set up of the particular model was adopted from the UCLA (2) studies, which in turn has provided a means of comparison. The reinforced earth wall models were build inside a plywood box 30 in. (76 cm) wide, 40 in. (101.6cm) long and 24 in. (61cm) high with a plexiglass wall for observation. The testing procedure was presented in detail by Espinosa (1).

The model walls were built vertically utilizing fine sand, aluminum reinforcing strips (ties) and aluminum sheet panels as skin. The reinforcing ties were cut from common household aluminum foil 0.00063 in. (0.016mm) thick at a width of 0.158 in. (4.05mm). Ten samples of these ties were tested to failure under tension, yielding an average tensile strength of 0.924 lb. (0.419 kg). Two different tie lengths 6 in. (152.4mm) and 11.5 in. (292mm) were used. The aluminum panels comprising the skin were 30 in. (76.2cm) long extending over the full width of the box. The individual panel sheets were 1.25 in. (31.8mm) and 2.5 in. (63.5mm) in height and 1/32 in. (0.79mm) in thickness. Skin and tie elements were connected by cellophane tape which proved to be adequate. The model tests incorporated vertical spacing (x) of the ties at 0.833 in. (21.2mm), 1.25 in. (31.5mm) and 2.5 in. (63mm) for both 11.5 in. (292mm) and 6 in. (152.4mm) tie lengths (L).

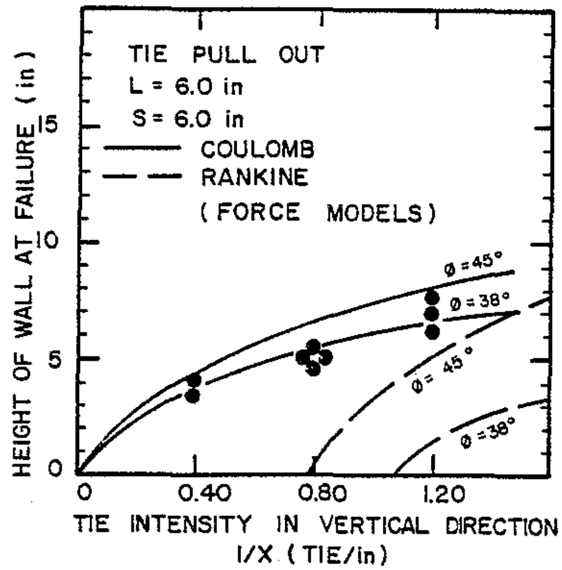

Fig. 1 - Height of Model Wall at Failure by Tie Pull-Out

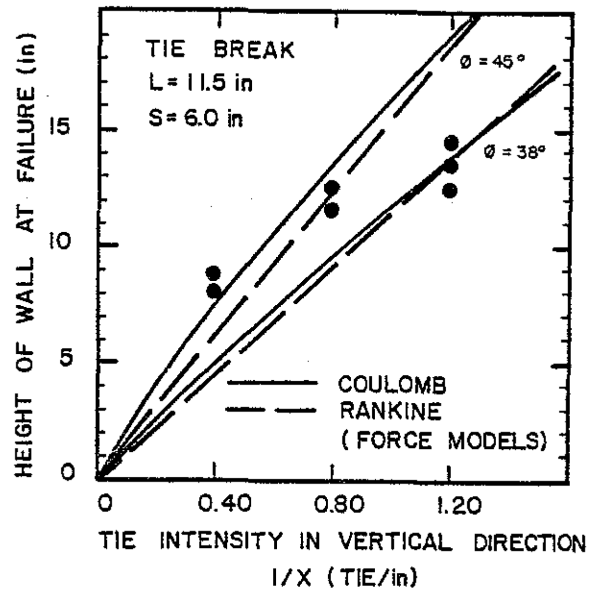

Fig. 2 - Height of Model Wall at Failure by Tie Breakage

The soil selected as backfill material was uniform fine sand (SP) with subangular grains; D_{50} = 0.0157 in. (0.40mm) and coefficient of uniformity of 1.68. The average in place density was 1,610 kg/m^3 (100.5 p.c.f) corresponding to a relative density of D_r = 63.5%, with γ_{max} = 1,720 kg/m^3 (107.3 p.c.f) and γ_{min} = 1,450 kg/m^3 (90.5 p.c.f). Water content was measured to be 0%. The angle of internal friction (ϕ) of the material at placement density was investigated by performing a series of standard direct shear tests over a range of normal stresses and it was observed that ϕ = 45° for the range of 0.2 - 1.1 p.s.i (1.38 - 7.59 kN/m^2) corresponding to the stress levels encountered in the model tests. However, for the range of normal stresses 7.1 - 14.2 p.s.i. (48.99 - 97.98 kN/m^2) which is more representative of the field conditions, ϕ was established to be 38°. The sand was placed in the box in a uniform manner with the raining technique (1, 2).

The friction angle (ϕ_μ) between aluminum foil and sand at placement density was investigated performing two different direct shear tests. In one series, aluminum foil (sheet) was sandwiched in sand at the level of controlled plane of shearing, yielding $\phi\mu$ = 35.5° for the normal stress of 0.2 - 1.1 p.s.i (1.38 - 7.59 kN/m^2). In the other series, aluminum foil was wrapped around a wooden block which then was fitted into the lower half of the shear box with sand at model placement density in the upper half. These tests have yielded $\phi\mu$ = 25.1° - 26.5° for the same normal stress range.

The significance of level of normal stress as well as method of testing on parameters ϕ and ϕ_μ has been discussed by Soydemir and Espinosa (9).

CURRENT DESIGN FORMULATIONS

In line with the modes of failure specified, proposed current formulations for the design of reinforced earth retaining walls are based on Coulomb and Rankine earth pressure theories. (2, 3, 4, 6)

For the mode of failure by tie breakage;

Coulomb Force Model:

$$H_f = \frac{(n+1)}{n} \frac{T_m}{K_A \gamma s} \frac{1}{x} \qquad (1)$$

Rankine Force Model:

$$H_f = \frac{T_m}{K_A \gamma s} \frac{1}{x} \qquad (2)$$

and for the mode of failure by tie pull-out;

Coulomb Force Model:

$$H_f = \left\{\frac{4\ x\ w \tan \phi_\mu}{K_A\ s} \sum_{i=1}^{n} i\left(L - (n-i)\ x \tan\left(45 - \frac{\phi}{2}\right)\right)\right\}^{\frac{1}{2}} \qquad (3)$$

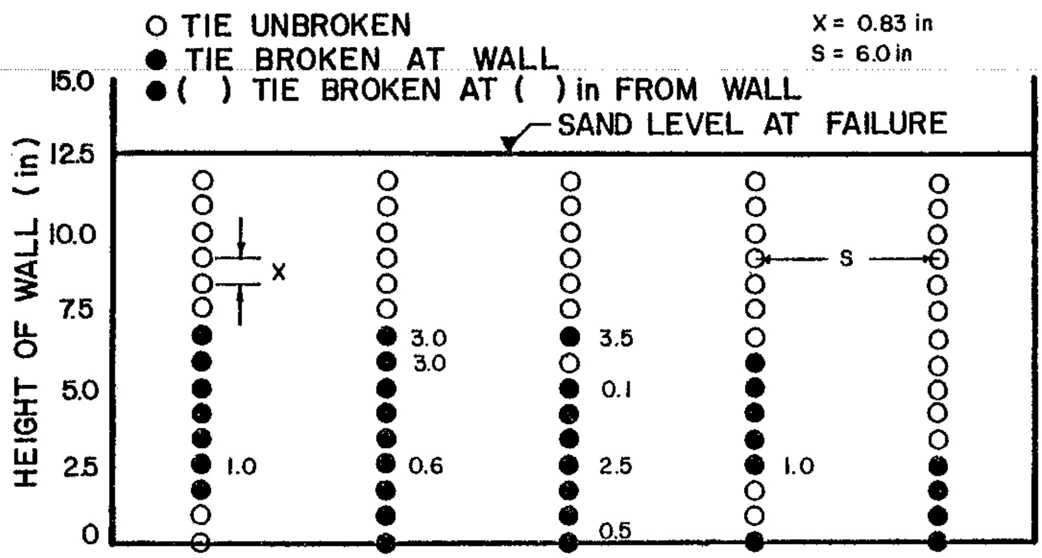

Fig. 3 - Typical Tie Breakage Configuration at Failure

Rankine Model:

$$H_f = \tan\left(45 + \frac{\phi}{2}\right)\left(L - \frac{s \times K_A}{2\, w \tan \phi_\mu}\right) \qquad (4)$$

are utilized. In these formulations;

H_f: height of wall failure

ϕ : angle of internal friction for backfill

K_A: coefficient of active earth pressure

ϕ_μ: angle of friction between backfill and ties

s : horizontal spacing of ties

x : vertical spacing of ties

L : length of ties

w : width of ties

T_m: tensile strength of ties

n : number of ties in the wall

TEST DATA

Pull-Out Tests

Date are presented in Fig. 1 with respect to (Height of Wall at Failure) v.s 1/x (Tie Intensity in Vertical Direction). For these tests with tie length L = 6 in. (152mm) all model walls failed by tie pull-out with no visible damage of the ties. Also in Fig. 1, Coulomb (Eq. 3) and Rankine (Eq. 4) Force Models for the mode of failure by tie pull-out are incorporated. Eq. 3 and Eq. 4 are plotted for $\phi = 45^\circ$ and 38°, with ϕ_μ selected as 35.5°.

Fig. 1 reveals that the Coulomb Force Model (Eq. 3) agrees reasonably well with the observed model behavior, however, Rankine Force Model (Eq. 4) exhibits a basic deficiency.

Tie Break Tests

Data are presented in Fig. 2 with respect to (Height of Wall at Failure) v.s 1/x (Tie Intensity in Vertical Direction). For these tests with tie length L = 11.5 in. (292mm) all model walls failed by tie break. Also in Fig. 2, Coulomb (Eq. 1) and Rankine (Eq. 2) Force Models for the mode of failure by tie breakage are incorporated. Eq. 1 and Eq. 2 are plotted for $\phi = 45^\circ$ and 38°. It may be observed that for a relatively large number of ties (n) in the vertical extent, the two models are essentially identical.

Fig. 2 reveals that even though there seems to be a general agreement, the mathematical models do not reflect the inherent nonlinearity exhibited by the model wall tests. It appears that this nonlinearity becomes more significant with increasing tie intensity in the vertical direction.

In Fig. 3 a typical pattern of tie breaks at failure is presented. It is to be noted that not all ties break at failure as assumed in developing the associated mathematical models. It appears that ties under relatively higher normal stresses at lower elevations fail by breaking whereas ties at higher elevations fail by pull-out, thus essentially a "composite" failure is generated. It is likely that inherent nonlinearity exhibited in Fig. 2 is due to the "composite" nature of the failure. It is also observed that tie breakage essentially occurs at or very near the wall.

General Observations

Observed test data on model walls agree quite well with data previously reported by Lee et al (2) where horizontal spacing of ties (s) was selected as the variable parameter with vertical spacing of ties (x) kept constant at 1 in. (25.4mm).

For all failures, a failure wedge was clearly identified by means of placing very thin layers of colored sand during backfilling. Orientation of failure planes were nearly $45^{0} + \phi/2$ from the horizontal at the base, becoming slightly more vertical with increasing height. Through video tape recordings it was also observed that failure wedge was developed progressively, initiated at the lower most region similar to local yielding and gradually moving upward (1).

ACKNOWLEDGEMENTS

The study was undertaken while the principal author was a Visiting Associate Professor at Rensselaer Polytechnic Institute (1977). Mr. A. Espinosa was a Graduate Research Assistant with the Civil Engineering Department. The Reinforced Earth Company, Washington, D.C. and UCLA Library are appreciated for supplementing relevant information.

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