The mechanics of repeated loading mobilisation in earth reinforcing element

Mécanismes de répartitions d'un chargement répété dans un élément de renforcement de sol

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ABSTRACT: The mechanics of load mobilisation in earth reinforcing elements during the loading and unloading states has been examined. It is argued that as a reinforcing element is loaded the resistance available at the reinforcement-soil interface is gradually mobilised along its surface. Based on this reasoning, a theoretical study of load transfer and reinforcement displacement for both loading and unloading states has been developed. The obtained results explains why cyclic loading of an earth reinforcing element to a constant load level induces permanent displacement of this element.

RESUME: Les mécanismes de distribution des contraintes dans un élément de renforcement en terre armée lors d'un chargement - déchargement ont été examinés. Il a été argumenté que, lors du chargement d'un élément de renforcement, la résistance à l'interface sol-renforcement se répartie graduellement le long de la surface du renforcement. En se basant sur ce principe, une étude théorique a été développée examinant les mécanismes de répartitions des contraintes et des déplacements. Les résultats obtenus montrent, en effet, qu'un chargement cyclique d'un élément de renforcement à un niveau constant provoque des déplacements permanents de cet élément.

1 INTRODUCTION

For the last 25 years, the practice of reinforcing soils for retaining-wall structures has increased remarkably in a range of geotechnical applications. Several forms of reinforcing elements have been used, namely: steel strips, geotextiles, polymer grids and steel grids. The design philosophy and methodology developed for reinforced earth retaining structures derives primarily from research related to strip-reinforced retaining structures. A reinforced earth element is a tensile member embedded in a soil mass. Under applied external load the reinforcement will mobilise resistance along its length according to the laws of band and bearing. For computational convenience, this resistance has been separated into a skin friction component and a passive-bearing component. Although it has been known that these components are interrelated and strain-dependent with the friction load mobilisation at a small fraction of the displacement required for mobilisation of the bearing component (Touahmia & Hanna, 1991), little study has been made at understanding the mechanics of mobilisation of these components during the loading and unloading states. It is considered that the mechanics of the soil-reinforcement interface when understood will enable a reinforcement load test to be interpreted with confidence. The proposed paper provides a simple means of examining the mechanics of load transfer and reinforcement displacement during both loading and unloading of the reinforcing element.

2 MECHANICS OF LOAD MOBILISATION

Every branch of engineering is concerned with friction. In the case of earth reinforcing elements which are in direct contact with a soil mass, force is transmitted from one material to the other when relative movement takes place between them. This transmission of force through the contact surface or interface zone is called skin friction. The term 'adhesion' is usually used when referring to the skin friction developed on a reinforcement surface.

Let the soil adhesion at the interface be $\delta_a(x)$ where x is the distance measured from the reinforcing element front. This adhesion is developed in the soil mass at a small distance from the reinforcement surface. Because the reinforcing element is flexible the gross failure mechanism must be examined. This is possible by extending the local failure mechanism already put forward. Consider a reinforcing element which is subjected to incremental loading and unloading. The first increment of load applied to the reinforcement (ΔT_1) develops frictional resistance and passive-bearing resistance over the front part of the reinforcement length only, as showed in Figure 1(a). The back end of the reinforcement length remains unloaded. At some average adhesion the strength of the interface is mobilised and failure migrates along the reinforcement a distance Δl_1, as suggested in Figure1(a). Equilibrium of the reinforcement-soil system gives:

$$\Delta T_1 = \Delta F_1 + \Delta P_1 \tag{1}$$

where ΔF_1 and ΔP_1 are the frictional resistance and the passive-bearing resistance along the distance Δl_1 respectively.

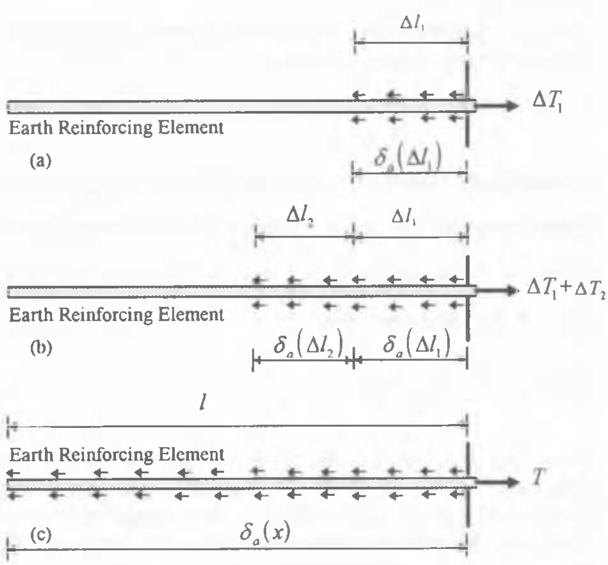

Figure 1. Load mobilisation along the earth reinforcing element due to incremental loading.

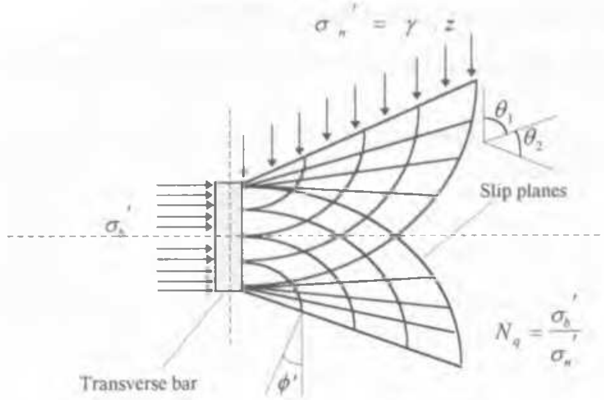

Figure 2. Punching Shear Failure (After Jewell et al, 1984).

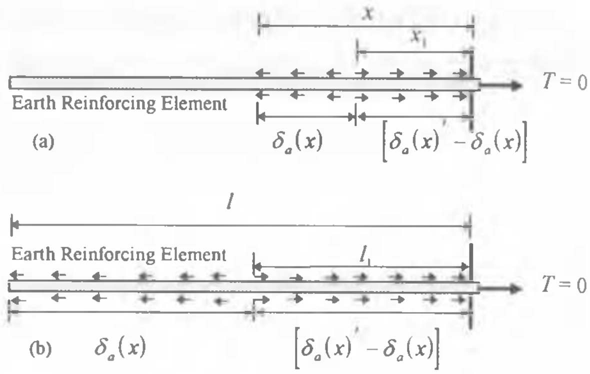

Figure 3. Residual stress condition after loading-unload sequence

The frictional resistance can be expressed as follows:

$$\Delta F_1 = \sigma_n \delta_a(\Delta l_1) 2b\Delta l_1 \qquad (2)$$

where σ_n is the applied normal pressure at the soil-reinforcement interface and b is the reinforcement width.

The passive-bearing resistance is evaluated by bearing capacity theory and can be expressed as follows:

$$\Delta P_i = \left[\sigma_n N_q + CN_c\right] m_i \qquad (3)$$

where N_q and N_c are the bearing-capacity factors, C is the cohesion of the backfill soil and m_i is the number of bearing members over the distance Δl_1. Different assumptions have been used for determining the bearing-capacity factors. Jewell et al. (1984) assumed a punching-failure mode for reinforcement passive-bearing resistance as shown in Figure 2. The expressions for bearing-capacity factors are:

$$N_q = \exp\left[\left(\frac{\pi}{2} + \phi\right)\tan\phi\right]\tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \qquad (3a)$$

$$N_c = \left(N_q - 1\right)\cot\phi \qquad (3b)$$

where ϕ is the friction angle of soil.

An additional load increment ΔT_2 (Figure 1(b)) causes failure over an additional reinforcement length Δl_2. Provided the failed region Δl_1 cannot develop an adhesion greater than $\delta_a(\Delta l_1)$, equilibrium of the reinforcement gives:

$$\Delta T_2 = \Delta F_2 + \Delta P_2 \qquad (4)$$

by incrementally increasing the applied load to $T = \sum_{i=1}^{n} \Delta T_i$, the frictional resistance over the full length of the reinforcing element becomes $F = 2b\sigma_n \int_0^{l} \delta_a(x)dx$, and equilibrium of the reinforcement-soil system gives:

$$T = 2b\sigma_n \int_0^{l} \delta_a(x)dx + \sum_{i=1}^{n} \Delta P_i \qquad (5)$$

The unloading of the reinforcement may be studied by incrementally adding a reverse or negative loads. Thus, the mechanics of unloading are similar to those described for the loading case, except the adhesion resistance is no longer $\delta_a(x)$ but $\delta_a(x)'$ where $\delta_a(x)' \geq \delta_a(x)$. Initially the adhesion $\delta_a(x)$ in the direction of the reverse load is overcome and this is followed by the mobilisation of the adhesion $\left[\delta_a(x)' - \delta_a(x)\right]$ needed to cause failure in the reverse direction (Figure 3).

Reverse movements develop to a distance x_1 such that under no load an equilibrium state develops which is given by:

$$2b\sigma_n \int_0^{l} \delta_a(x)dx + \sum_{i=1}^{n} \Delta P_i dx = 2b\sigma_n \int_0^{l_1} \delta_a(x)' dx \qquad (6)$$

Thus the process of unloading may be studied by the gradual application of a negative load until the gross effect is that of zero external applied load (Figure 3).

3 MECHANICS OF REINFORCEMENT DISPLACEMENT

Two quantities are of interest, the displacement of the reinforcing element under load and under zero applied load. In the following treatment it is assumed that the adhesion at the reinforcement interface is uniform and equals to $\delta_a(x)$ during loading and $\zeta_a(x)$ during unloading. As mentioned above the value of $\zeta_a(x)$ includes the overcoming of the initial effect of loading. The frictional loads developed along the reinforcing element under load and under zero applied load are then:

$$F = 2b\sigma_n \delta_a(x)x \qquad (7)$$

$$F' = 2b\sigma_n \zeta_a(x)x \qquad (8)$$

At an applied load T, adhesion is mobilised over a length x. Increase of T by ΔT causes an additional displacement $d\Delta$ of the reinforcing element. This incremental displacement maybe expressed by:

$$d\Delta = \frac{\Delta Fx}{\varpi} + \frac{\Delta Px}{\varpi} \qquad (9)$$

where P is the load taken by the bearing members of the reinforcing element and is constant which depends on the reinforcement stiffenss and properties. Putting $\Delta F = \alpha\Delta P$ and rearranging Equation (7) gives:

$$d\Delta = \frac{F}{2b\sigma_n \delta_a(x)\varpi}\Delta F\left(1 + \frac{1}{\alpha}\right) \qquad (10)$$

which on integration between $F = 0$ and F gives:

$$\Delta = \frac{F^2}{4b\sigma_n \delta_a(x)\varpi}\left(1 + \frac{1}{\alpha}\right) \qquad (11)$$

Therefore the form of the load-deformation diagram is quadratic when the adhesion is constant along the reinforcing element (Figure 4).

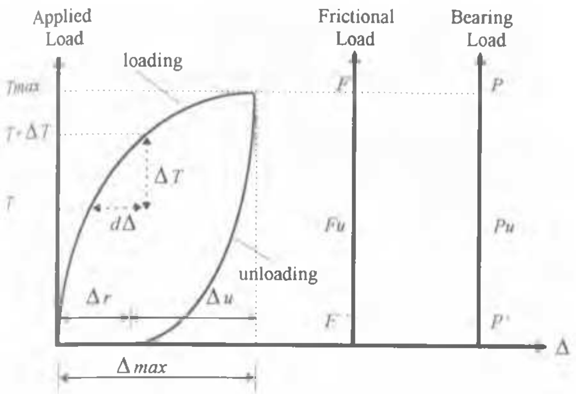

Fig.4. Load-displacement Diagram

An examination of the unload diagram is possible by similar reasoning. If the reinforcing element is under a load T_{max} which transfers F_{max} in adhesion and P_{max} in bearing with a corresponding displacement of the reinforcement front Δ_{max}, then the unloading of the reinforcing element by an amount of T_u causes a reverse displacement Δ_u and a load transfer change of F_u in friction and P_u in bearing. The load still transferred by the reinforcement to the soil in adhesion is F' and in bearing is P' and the corresponding deflection of the reinforcing element front under zero applied load is Δ_r (Figure 4).

As mentioned in Figure 4, on reloading, the displacement may not equal the original displacement which resulted on first loading unless the interface adhesion remains constant. This explains why cyclic loading of an earth reinforcing element to a constant load level causes progressive pullout of the reinforcement (Touahmia and Hanna, 1991).

Following from equation (11):

$$\Delta_{max} = \frac{F^2_{max}}{4b\sigma_n\delta_a(x)\varpi}\left(1+\frac{1}{\alpha}\right) \tag{12}$$

and

$$\Delta_u = \frac{F_u^2}{4b\sigma_n\zeta_a(x)\varpi}\left(1+\frac{1}{\alpha}\right) \tag{13}$$

Hence,

$$\Delta_r = \Delta_{max} - \Delta_u = \frac{1}{4b\sigma_n\varpi}\left(1+\frac{1}{\alpha}\right)\left[\frac{F^2_{max}}{\delta_a(x)} - \frac{F^2_u}{\zeta_a(x)}\right] \tag{14}$$

where Δ_r is the residual displacement under zero applied load as shown in Figure 4.

4 CONCLUSION

The mechanics of load mobilisation and displacement of an earth reinforcing element under loading and unloading conditions has been examined. It is suggested that as a reinforcing element is loaded the pullout resistance available at the reinforcement-soil interface is gradually mobilized along the reinforcement length. Based on this reasoning, a simple theory has been developed. The results showed that the loading-unloading behaviour of a reinforcement is non-linear. Because of the energy loss in the loading-unloading diagram, a residual displacement results under zero applied load. This means that cyclic loading of an earth reinforcing element to a constant load level induces permanent displacement of the element.

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