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# Analysis of soil-welded steel mesh reinforcement interface interaction by pull-out tests

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ABSTRACT

The interface friction coefficient is an important design parameter for reinforced soil structures where the friction between the soil and reinforcement elements is mobilized. The pull-out test is the most commonly adopted method to identify this friction coefficient. In this paper, 18 pull-out tests were conducted on two types of welded steel meshes (normal and dense mesh) embedded in a sand to investigate the soil/reinforcement interaction. The tests were conducted under vertical stresses ranging from 20 to 140 kPa on the reinforcement. The French standard (NF P 94-270, 2009) uses an analytical method to predict the friction coefficient. The comparison with the experimental results agrees reasonably well. Ju et al. (2004) developed a new test method based on a staged pull-out test for extensible reinforcements. In this study and for inextensible reinforcement, this new test method has also been used. In a usual pull-out test, only one vertical stress has been used. For a staged pull-out test, several vertical stresses are used. The results of staged pull-out tests are in good agreement with results of usual pull-out test.



## 1. Introduction

The stabilization of soil with inclusions is an ancient technique. For mechanically stabilized earth (MSE), the first setup (Haeri et al., 2000) has been done by Henry Vidal in 1961. In an MSE structure (e.g., reinforced retaining wall, reinforced embankment, or reinforced soil), reinforcements are placed horizontally in granular soil layers that are normally used as backfill or embankment material. Recent research involving MSE and reinforced embankments have been reported by many researchers (e.g., Abdelouhab et al., 2010, 2011; Bathurst et al., 2005; Bergado and Teerawattanasuk, 2008; Chen et al., 2007; Esfandiari and Selamat, 2012; Hufenus et al., 2006; Li and Rowe, 2008; Nouri et al., 2006; Palmeira, 2009; Rowe and Skinner, 2001; Sieira et al., 2009; Skinner and Rowe, 2005a,b; Varuso et al., 2005).

Materials used in reinforcement elements include steel, polymeric materials and even bamboo. Considering theirs modulus, the reinforcement materials can be classified into two types: inextensible materials and extensible materials. Inextensible materials are wire mesh, steel strip, bar mat, and welded wire or steel mesh. Extensible reinforcement includes non-metallic material such as geosynthetics (Tin et al., 2011).

The stability of earth structures depends on the interaction between soil and reinforcement. Soil/reinforcement interaction makes an important role to determine the length of the reinforcement and the distance between the upper and lower reinforcements (Ju et al., 2004). A pull-out test allows to simulate the tensile stress applied on the reinforcement and to define the evolution of the interface parameters during its mobilisation (Khedkar and Mandal, 2009; Lajevardi 2013; Palmeira, 2009; Sieira et al., 2009; Su et al., 2008). Unlike the direct shear test, the pull-out test highlights the evolution of several parameters: shear stress and friction along the soil/reinforcement interface; the soil dilatancy and the reinforcement strain (Abdelouhab et al., 2010). These parameters are taken into account in several design methods of MSE walls (e.g. French standard: NF P 94-270, 2009). The pull-out mechanisms of various inextensible reinforcements have been investigated not only by full-scale and laboratory model tests, but also by numerical methods (e.g., Abdelouhab et al., 2011; Abdi and Arjomand, 2011; Abdi et al., 2009; Alagiyawanna et al., 2001; Desai and Hoseiny, 2005; Dias et al., 2002; Goodhue et al., 2001; Gurung, 2001; Moraci and Cardile, 2009, 2012; Moraci and Gioffre, 2006; Palmeira and Milligan, 1989; Subaida et al., 2008; Sugimoto, 2003; Yin et al., 2008; Zhou et al., 2011).

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The use of inextensible reinforcements (polymeric or steel grids) to stabilize earth structures has grown rapidly in the world. When used for retaining walls or steep slopes, they can be laid continuously along the width of the reinforced soil system (grid or mesh type) or laid at intervals (strip type). Many researchers (Bergado et al., 1987; Khedkar and Mandal 2009; Nernheim, 2005; Palmeira and Milligan, 1989) made clear that geometry of the reinforcement is one of the important factors in pull-out study. The advantage of the steel mesh reinforcement is that the pull-out bearing resistance in the resistant zone is high. However, the total volume (weight) of steel mesh required is still high due to wasted transverse (bearing) bars in the active (unstable) zone (Horpibulsuki and Niramitkornburee, 2010). The pull-out resistance mechanisms of steel mesh reinforcement have been extensively studied by many researchers (Bergado et al., 1988, 1996; Chai, 1992; Horpibulsuki and Niramitkornburee, 2010; Jayawickrama et al., 2012; Jewell et al., 1984; Lawson et al., 2013; Palmeira, 2009; Palmeira and Milligan, 1989; Peterson and Anderson, 1980; Shivashankar, 1991; Suksiripattanapong et al., 2013; Tin et al., 2011). The overall configuration of the test systems used by different researchers remained the same.

Finite element method analyses usually assume mesh (grid) reinforcement as a continuous equivalent rough planar reinforcement. However, the pull-out response of this type of reinforcement is fundamentally dependent on shape and geometrical characteristics of the mesh, with particular reference to the transverse bearing members. A consequence of the influence of the mesh geometrical characteristics, of the interference between transverse members and the assumption of the mesh as a planar continuous element is that the apparent soil/mesh friction coefficient ($f^*$) becomes dependent on the length of the mesh, which complicates the estimate of soil/mesh bond for design purposes (Palmeira, 2009).

Pull-out tests are necessary in order to study the interaction behaviour between soil and reinforcement in the resistant (anchorage) zone; hence these properties have direct implications to the design of reinforced soil structures. In order to analyse the internal stability of reinforced earth structures, it is necessary to evaluate the pull-out resistance of reinforcement, mobilized in the resistant zone. The pull-out resistance in a pull-out test can be described by the following equations (Moraci and Recalcati 2006):

$$P_R = 2L\sigma'_v f_b \tan\varphi' = 2L\sigma'_v f^* = 2L\sigma'_v \alpha F^*$$

So:

$$f_b \tan\varphi' = f^* = \alpha F^*$$

where $P_R$ is the pull-out resistance (per unit width); $L$ the reinforcement length in the anchorage zone; $\sigma'_v$ the effective vertical stress; $\varphi'$ the soil friction angle; $f_b$ the soil/reinforcement pull-out interaction coefficient; $f^*$ the apparent friction coefficient; $F^*$ the pull-out resistance factor; $\alpha$ the scale effect correction factor taking into account for a non-linear stress reduction over the embedded length of highly extensible reinforcements (FHWA, 2001).

The soil/reinforcement pull-out interaction coefficient $f_b$ may be determined by means of theoretical expressions (Jewell et al., 1985), whose limits have been investigated by different researchers (Ghionna et al., 2001; Moraci and Montanelli, 2000; Palmeira and Milligan, 1989; Wilson-Fahmy and Koerner, 1993), or by back-calculation from pull-out test results. In this case previous experimental studies (Ghionna et al., 2001; Moraci and Montanelli, 2000; Palmeira and Milligan, 1989) have shown that the values of $f_b$ are largely influenced by the choice of the value of the soil friction angle.

According to FHWA (2001) the scale effect correction factor $\alpha$ can be obtained from pull-out tests on reinforcements with different lengths or derived using analytical or numerical load transfer models which have been "calibrated" through numerical test simulations. In the absence of test data, $\alpha = 1$ for steel reinforcements, $\alpha = 0.8$ for geogrids and 0.6 for geotextiles can be taken.

In absence of a clear indication regarding the choice of the soil friction angle to be used for the determination of $f_b$ and to avoid the use of sophisticated numerical analyses, the problem of the determination of the pull-out resistance may be overcome by the use of the soil/reinforcement interface apparent friction coefficient using the following equation that depends on the vertical stress:

$$f^* = P_R \Big/ \left(2L\sigma'_v\right)$$

It is important to note that the determination of $f^*$ using above equation can be performed without any assumption about the values of the soil friction angle at the interface and with an assuming that the friction occurs on both sides of the reinforcement.

Conservative default values for $f^*$ are provided by the French standard guideline (NF P 94-270, 2009) to be used in the absence of pull-out test data (Table 1).

This standard provides for different types of reinforcements, the default value of $f^*$ which depends on the type of reinforcement (strip or mesh and extensible or inextensible) and for the geotechnical characteristics of the backfill (for example: $C_u$ and $\varphi$). Fig. 1 shows the variation of maximum friction coefficient $f_0{}^*$ at the top of the wall (where $\sigma_v = 0$) and the maximum friction coefficient $f_1{}^*$ at a depth of 6 m and below (where $\sigma_v = 120$ kPa). The soil and the welded steel mesh reinforcement used in this figure are a granular soil (sand) with a normal ($t = 0.8$ cm and $S_t = 50.5$ cm) and dense ($t = 0.8$ cm and $S_t = 14$ cm) welded steel mesh respectively (presented later in this paper). It can be seen that steel strips reinforcement are the soil reinforcement type with most pull-out resistance. Welded steel mesh reinforcement, on the other hand, offers the least reinforcement.

On a construction site where rigid inclusions reinforcements were used in Poland (Gdansk), two types of welded steel mesh were installed in sand. In order to validate the characteristics of the interface between sand and welded steel mesh considered for the improved soil mass design a qualification survey was carried out. The pull-out tests have been carried out with two types of welded steel meshes (normal and dense) in a Polish sand. The purpose of the work was the qualification of the apparent friction coefficient and a comparison with the results obtained from the French standard. This standard has been compared with another one. Two pull-out test methods have been used. Different levels of vertical stress were simulated (20 kPa–140 kPa) to recreate the on site stress conditions of an embankment with a variable height (from 0 to 7 m). The influence of the type of reinforcement and the influence of vertical stress were studied based on the pull-out tests.

**Table 1**
Default values for the apparent friction coefficient.

| Type of reinforcement | | $f^*$ | |
|---|---|---|---|
| | | Top of wall | Depth of 6 m and below |
| Steel | Strip | $1.2 + \log C_u$ | Min (0.8, $\tan\varphi$) |
| | Mesh | $17.5\ (t/S_t)$ | $7.5\ (t/S_t)$ |
| | Smooth | 0.4 | 0.4 |
| Geosynthetic | Strip | 1.1 | $0.8 \tan\varphi$ |
| | Sheet | $(0.5–1) \tan\varphi$ | $(0.5–1) \tan\varphi$ |

$t$ = Diameter of the transverse bar, $S_t$ = Transverse bar spacing, $C_u$ = Uniformity coefficient of the backfill, $\varphi$ = Angle of internal friction for backfill.