Analysis of Load-Settlement Relationship for Unpaved Road Reinforced with Geogrid

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ABSTRACT: Taking into account of the model test results, the surface settlement of an unpaved road reinforced, to improve its safety, with geogrid placed at the granular fill-soft earth interface is analyzed under wheel load. The relationship between the surface settlement and the contact pressure of tire is derived, which can be used to estimate the bearing capacity corresponding to a given surface settlement for a given geogrid-reinforced unpaved road, or to calculate the proper thickness of the granular fill layer and the necessary tensile strength or tensile modulus of the geogrid for such a road.

1 INTRODUCTION

As a method to improve the safety of soil structures, geogrid reinforcement is widely used, especially in those containing a layer of granular fill overlying soft ground, such as unpaved roads, embankments, and car parks, etc., where, usually, a layer of reinforcement is placed at the fill-soft soil interface. Several researchers have conducted experimental studies on such a system (Love et al. 1987; Fammin and Sigurdsson 1996). A number of procedures have been proposed for geotextile-reinforcement unpaved roads, notably by Giroud and Noiray (1981). For geogrid-reinforced unpaved roads, a theoretical method has been proposed by Giroad and Han (2004). All of them are based on the assumption that general shear failure will occur in the soft subgrade soil if the pressure at the top of the subgrade soil. This idea is supported by the observations in laboratory tests performed by Love et al. (1987). However, when such a failure occurs, the displacement of the system is usually unacceptable. If the deformation of the reinforcement layer is small, a solution has been proposed by Wan Tao and Wang Zhao (2003).

The purpose of this paper is to analyze the load-settlement relationship of an unpaved road that consists of a layer of granular fill overlying soft subgrade soil with a geogrid at the fill-subgrade interface under working conditions. In this situation of such a system, the general shear failure is not permissible in the soft subsoil, and the deformation of the geogrid is commonly not small. So the analytical method by Giroud and Noiray (1981) or that by Wan Tao and Wang Zhao (2003) mentioned above is not rational to explain the problem discussed here. Therefore, the behavior under working conditions for the above system is to be studied in order to get the load-settlement relationship. Once the load-settlement curve is obtained, the bearing capacity under permissible settlement of this system can evaluated, or for a given load, the geogrid with suitable tensile strength and stiffness is easily selected for the structure; or an appropriate thickness of the fill is determined for a supplied geogrid.

The similar idea mentioned above has been discussed under plain strain conditions in another paper (Hu 1996a). So, the analysis presented herein is to be focused on axis symmetrical problem, taking into account the model test results (Hu 1996b), which will be introduced briefly in the following sections.

2 BRIEF DESCRIPTION OF MODEL TESTS

Hoping to provide some further data concerning the behavior of unpaved road with a geogrid inclusion, the author has carried out a series of model tests under plane conditions with a 0.2 m wide footing on a 0.09 m thick layer of gravel fill over a 0.4 m thick stratum of soft clay with or without a geogrid at the gravel-clay interface.

Details of the apparatus and the test procedures have been given by Hu (1996b). Briefly, the tests were carried out in a rigid box of internal length 0.8 m, width 0.26 m, and depth 0.6 m. On the back of the front wall, which was made of Plexiglas and stiffened by two angle bars, a coordinate system was engraved slightly. The subsoil, which was reconstituted clay with basic properties presented in Table 1, and consolidation test results in Table 2, was compacted in three layers. On the surface of every layer, small markers, which were the sharp-end parts of pins, were embedded close to the Plexiglas. A plastic grid produced by Netlon Ltd. Was used with a mass per unit area of 660 g/m2, and tensile strength of 5.4 kN/m at 10% strain. The material of the fill layer was a crushed stone with an average grain diameter of 20 mm, and unit weight of 21.0 kN/m3.

Table 1 Properties of clay used in tests

Property	Value
Plastic limit, w_P/%	19.7
Liquid limit, w_L/%	31.2
Water content, w/%	31.0
Unit weight, γ/kN/m^3	18.9
Apparent cohesion, c_u/kPa	5.0
Apparent angle of internal friction, ϕ_u/^{o}	2.5

Table 2 Consolidation test results of clay used in tests

Pressure/kPa	0	50	100	200	300	400
Void ratio	0.88	0.73	0.70	0.64	0.62	0.60

The footing load applied by a lever in increment of 11.3 kPa, and the resulting footing displacement measured by two dial gauges, placed at opposite corners of the footing. When the displacement varied less than 0.05 mm per hour at one level of pressure, another increment was added. The process is repeated for several increments of load until the footing displacement exceeded 60 mm or failure occurred in the subsoil. Before every incremental load was applied, the positions of the small markers mentioned above were recorded by means of the coordinate system on the Plexiglas and a coordinate microscope with 0.01 mm sensitivity. Thus the displacement field of the subsoil can be obtained. Such a displacement tracing method was first brought into use in laboratory by Liu et al. (1989). In order to determine the load-spread angle in the gravel fill, the shape of the geogrid after tests was examined after removing the gravel fill.

The displacement fields with and without geogrid and the footing pressure-settlement curves for reinforced and unreinforced systems were given in detail in another paper (Hu 1996b). The test results confirmed the following effects of the geogrid-reinforcement: (1) load-spreading effect; (2) tensioned-membrane support; and (3) lateral restraint. It was found that the lateral restraint effect was so strong to lead the subsoil vertically below the footing nearly no lateral moving. That is to say the subsoil is confined by the geogrid. In addition, the load-spread angle of the gravel fill, found in the experiment, is about 38° .

3 THEORETICAL ANALYSIS

Based on the above test results, a model, shown in Fig. 1, for an aggregate-geogrid-soft subgrade system is suggested here, in which the load-spreading effect and the tensioned-membrane support are included after Giroud and Noiray's approach (Giroud & Noiray 1981), and the lateral restraint of the subgrade is taken into account by assuming the subgrade soil vertically below the footing is in confined conditions. In the model, the wheel load is assumed a uniform circular pressure.

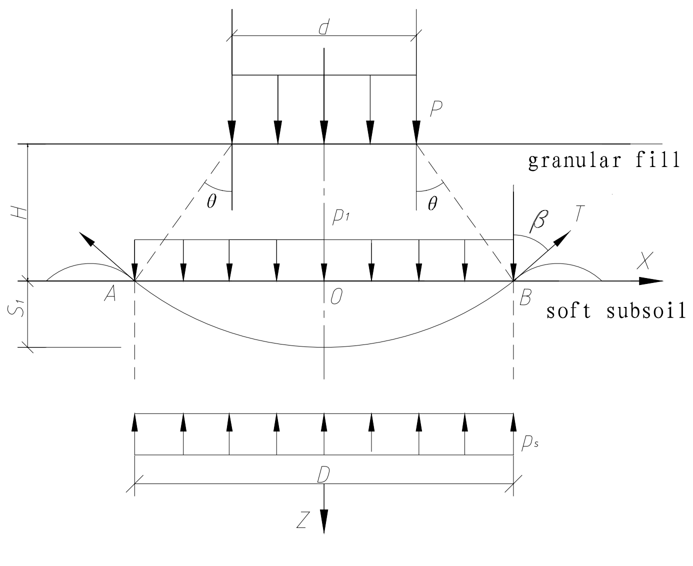

Fig. 1 Model for geogrid-reinforced unpaved road

where p = contact pressure between wheel and aggregate layer, which is approximately equal to the internal pressure of the wheel; d = diameter of wheel-ground contacting area; p_1 = pressure on geogrid-reinforcement layer; p_s = contact pressure between geogrid-reinforcement layer and subgrade; θ = load-spread angle in aggregate layer; and T = tension force in geogrid.

From the model showing in Fig. 1, we get the following relationships.

$$D = d + 2H\tan\theta \tag{1}$$

$$p_s = p\left(\frac{d}{D}\right)^2 + \gamma_0 H - \frac{4T\cos\beta}{D} \tag{2}$$

The shape of the deformed geogrid is assumed to represent portions of parabolas connected at A and B according to the model test results noted above (see Fig. 1), and it has the following equation

$$Z = -\frac{4S_1}{D^2}x^2 + S_1 \tag{3}$$

T is calculated by the following equation:

$$T = E_g \varepsilon_g \tag{4}$$

where ε_g = geogrid strain; E_g = geogrid modulus.

According to Eq. (3), ε_g and $\cos\beta$ are respectively expressed as follows:

$$\varepsilon_g = \frac{1}{2}\sqrt{1+m^2} + \frac{1}{2m}\ln(m + \sqrt{1+m^2}) - 1 \tag{5}$$

$$\cos\beta = \frac{1}{\sqrt{1+m^{-2}}} \tag{6}$$

$$m = \frac{4S_1}{D} \tag{7}$$

where γ_0 = aggregate unit weight.

In Eq. (2), $4T\cos\beta / D$ is the upward force provided by geogrid (Bai 1994).

The additional vertical stress induce in the subgrade soil due to p_s is derived from Boussinesq solution. And the relationship between p_s and S_1 is determined by the uniaxial compression assumption. Therefore, the following equations are obtained.

$$\sigma_z = p_s\left[\frac{1}{1+\frac{8}{3}\left(\frac{z}{D}\right)^2}\right] \quad (8)$$

$$S_1 = \frac{1}{E_s}\int_0^{z_0}\sigma_z dz \quad (9)$$

or

$$S_1 = \sqrt{\frac{3}{8}}\frac{D}{E_s}\arctan\left(\sqrt{\frac{8}{3}}\frac{z_0}{D}\right)p_s \quad (10)$$

where σ_z = additional vertical stress due to p_s at the depth of Z below the center of the area of p_s; E_s = mean constrained modulus of subsoil; Z_0 = settlement calculation depth, which is calculated from the following equation by assuming it is approximately equal to the depth in subgrade affected by wheel load P.

$$z_0 = \sqrt[3]{\frac{0 \cdot 5nP}{\gamma}} \quad (11)$$

where n = 5~10; γ = unit weight of subsoil. Generally, P = 100 kN; γ = 18 kN/m^3; n = 10 for soft subsoil, so Z_0 is commonly about 3 m.

Eq. (10) is based on the assumption that the subgrade soil is in confined conditions. But this assumption is a little different to the observation in model tests (Hu 1996b). According to Hu (1996a), Eq. (8) is modified as

$$S_1 = \psi\sqrt{\frac{3}{8}}\frac{D}{E_s}\arctan\left(\sqrt{\frac{8}{3}}\frac{Z_0}{D}\right)p_s \quad (12)$$

where ψ is a coefficient related to the constrained modulus of the subgrade soil. For soft subsoil, $\psi = 1.2$ (Hu 1996a).

In order to find out the relationship between the surface deflection, S, and soft ground settlement, S_1 (see Fig. 1), an assumption, showing in Fig. 2, is proposed here that V, which is the volume of the pit in the fill surface induced by the wheel pressure, p, is equal to V_1, which is the volume of pit in the soft ground surface. The shape of V is taken as cylinder with diameter d, and V_1 as a space formed by spinning parabola ***AB*** (see Fig. 1). Then the following equation is derived.

$$S_1 = 2\left(\frac{d}{D}\right)^2 S \quad (13)$$

Combining Eqs. (2), (12) and (13), the following relationship is given

$$p = 4\sqrt{\frac{2}{3}}\frac{E_s \cdot S}{\psi D\arctan\left(\sqrt{\frac{8}{3}}\frac{z_0}{D}\right)} - \gamma_0 H\left(\frac{D}{d}\right)^2 + \frac{4DT\cos\beta}{d^2} \quad (14)$$

For a given unpaved road on soft ground with geogrid reinforcement as described in this paper, the volume of H, γ_0, E_s in Eq. (14) and E_g in Eq. (4) are known, d is determined by the wheel load P and the internal pressure of the wheel, p. Therefore, when the surface settlement S is certain, S_1 and D can be deduced from Eq. (1) and Eq. (13). Then m is calculated by Eq. (7), $\cos\beta$ is determined by Eq. (6), and T is derived from Eq. (5) and Eq. (4). At last, the volume of p corresponding to the given S is obtained. According to such a procedure, the p-S curve is determined. On the other hand, if the thickness of the granular fill, H, is given, the corresponding permissible minimum of the geogrid modulus, E_{gmin}, can be determined by the equations presented in this paper

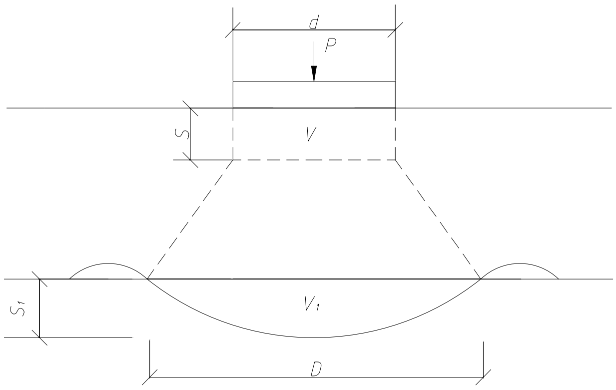

Fig. 2 Model for relationship of S and S_1

4 APPLICATION OF THE METHOD

An unpaved road, for example, consists a 0.2 m thick layer of crushed stone with unit weight of 21 kN/m^3, a soft-clay subgrade with unit weight of 18 kN/m^3 and average confined modulus of 630 kPa, and a geogrid with tensile modulus of 3.15 kN/m· %. If the load-spread angle of crushed stone, $\theta = 38^\circ$, $\psi = 1.2$, Z_0=3 m and d=0.3 m, the P-S curve is derived by the method presented here is showing if Fig. 3, where P is the wheel load, which is expressed by

$$P = \frac{1}{4}\pi d^2 p \tag{15}$$

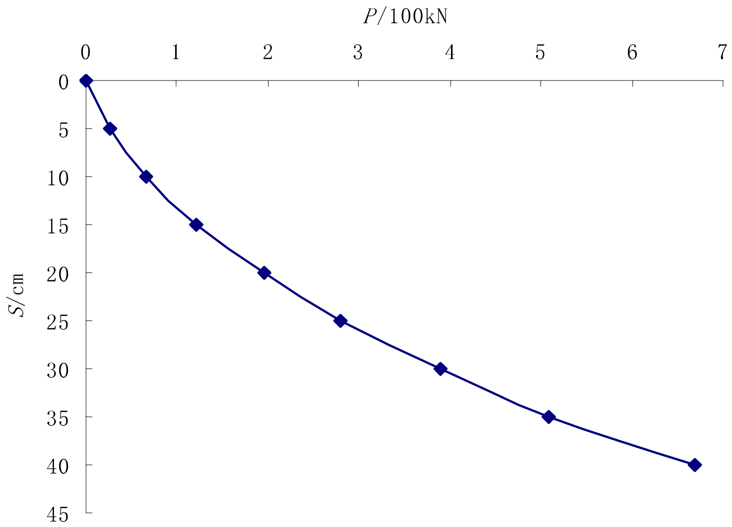

Fig. 3 P-S curve

5 CONCLUSION

For an unpaved road on soft ground with geogrid reinforcement, how to calculate settlement induced by wheel load is a key issue. The method presented in this paper is an answer of the problem. When the permissible surface settlement is given, the corresponding thickness of granular fill can be determined by the method if a certain geogrid is applied. On the other hand, while the thickness of granular fill is set, a geogrid with proper tensile modulus can be selected using the method noted here.

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