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DESIGN METHODOLOGY FOR STABILIZING SLOPES USING RECYCLED PLASTIC REINFORCEMENT

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ABSTRACT

Surficial slope failures, or nuisance slides, constitute a significant economic and manpower burden for many transportation agencies due to the frequent and recurring nature of the slides. A new method for stabilizing surficial slides using reinforcement manufactured from recycled plastics is being developed to provide agencies with a cost-effective alternative for stabilizing these slopes. As a part of this development, a design procedure has been established that draws upon previous experience with more conventional reinforcing materials such as concrete and steel, but with modifications to account for the reduced strength and stiffness of plastics. The design method follows a limit state design approach wherein a number of different limit states are considered, including failure of the reinforcing members, to establish the resisting force provided by the reinforcement. In this paper, the general design method is presented followed by more detailed coverage of each of the specific limit states that are considered in the design. Several design issues that remain to be addressed are also discussed.

INTRODUCTION

A new method for stabilization of surficial slope failures has been developed that utilizes slender recycled plastic members to reinforce and stabilize failed slopes. The

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application is similar to existing stabilization techniques such as soil nailing or soil doweling with conventional driven piles or drilled shafts. However, the application differs from the existing schemes because recycled plastic members have material and engineering properties that differ from those of more conventional members.

The plastic reinforcing members are manufactured from recycled plastic and other by-products. Recycled plastics are less susceptible to chemical and biological attack than other structural materials. However, modifications to current design procedures developed for similar techniques are needed to account for the reduced strength and increased ductility exhibited by plastic materials as compared to more conventional materials. Such a procedure is described in this paper.

GENERAL APPROACH TO STABILITY ANALYSIS

The general approach adopted for evaluating the stability of reinforced and unreinforced slopes is to first assume a potential sliding surface and then calculate a factor of safety for that sliding surface based on consideration of the equilibrium of the free body formed by the sliding surface and slope surface as shown in Fig. 1. The most common approach for doing so is to use a method of slices. In this approach, the sliding body is divided into a number of vertical slices and equilibrium of the individual slices is considered to determine the factor of safety for an assumed sliding surface. The process is then repeated for other potential sliding surfaces until the most critical sliding surface – the surface giving the lowest value of the factor of safety – is found. The factor of safety associated with the most critical sliding surface is taken to represent the stability of the slope.

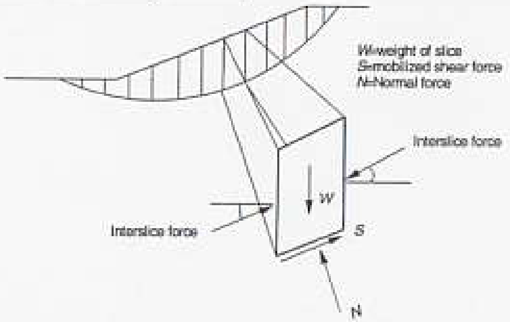

Figure 1 Static equilibrium of individual slice in the method of slices.

A similar approach is adopted for reinforced slopes except that a force due to a reinforcing member, F_R, is added to the other forces on slices that are intersected by reinforcing members as shown in Fig. 2. This force is included in development of equilibrium equations that are used to solve for the overall factor of safety. The reinforcement force (F_R) is considered a known quantity and must be provided for the stability analysis. The principal difficulty in analyzing reinforced slopes is thus establishing the magnitudes of these forces, rather than performing the stability analyses themselves. For limit equilibrium analyses, forces due to reinforcement are generally taken as the maximum resisting force that can be developed for the reinforcing element. The forces are therefore referred to as "limit resistances" in this paper. In general, the resisting force can have both axial and lateral components; only the lateral component of the resisting force is considered here.

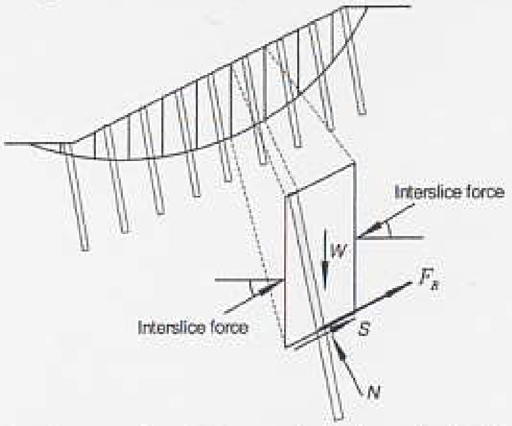

Figure 2 Reinforcement force (F_R) on a slice in the method of slices.

In general, the magnitude of the resisting force that is included in the stability analysis varies with position along the reinforcing member. A "limit resistance curve" is therefore needed to define the magnitude of the limit resistance as a function of location where a potential sliding surface crosses the member. As shown in Fig. 3, each reinforcing member on a slope provides a resisting force based on the location of the intersection of the sliding surface and the reinforcing member.

DEVELOPMENT OF LIMIT LATERAL RESISTANCE CURVES

The method for predicting the limit lateral resistance of individual reinforcing members uses a limit state design approach wherein a series of potential failure mechanisms are considered in developing the overall distribution of lateral resistance along a reinforcing member. The procedure is based on consideration of the following limit states:

- failure of soil around or between reinforcing members – referred to here as "Failure Mode 1",
- failure of soil due to insufficient anchorage length – referred to here as "Failure Mode 2", and
- structural failure of reinforcing members in shear or bending due to loads applied from the soil mass – referred to here as "Failure Mode 3".

In the method, separate limit resistance curves are developed for each limit state as illustrated in Fig. 4. From these individual curves, a "composite" limit resistance curve that corresponds to the most critical component of resistance at each sliding depth is established by taking the component with the least resistance (i.e. the critical failure mode) at each sliding depth.

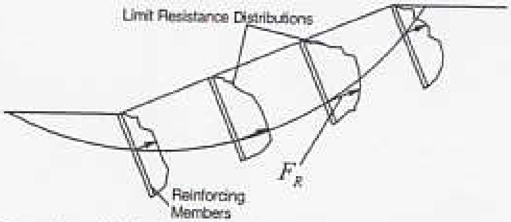

Figure 3 Example of limit resistance for multiple members in a slope.

Failure Mode 1 – Limit Soil Resistance

The first limit state considered is failure of the soil above the sliding surface by flow around or between reinforcing members. Calculation of the limit resistance for this failure mode requires that the lateral pressure at which failure of the soil will occur be known. This pressure is referred to as the "limit soil pressure" and is denoted p_u. Several alternative methods have been proposed for predicting the limit soil pressure for stabilizing piles (Parra et al., 2004). For the current work, the method proposed by Ito and Matsui (1975) was selected over other methods because it is flexible enough to be extended to members composed of non-conventional materials and because it is considered one of the more conservative of the available methods for typical member spacings. Other methods available for predicting the limit soil pressure are generally based on load tests for full-scale conventional steel and concrete piles, which are considerably different in size and stiffness than the recycled plastic members of primary concern in this paper.

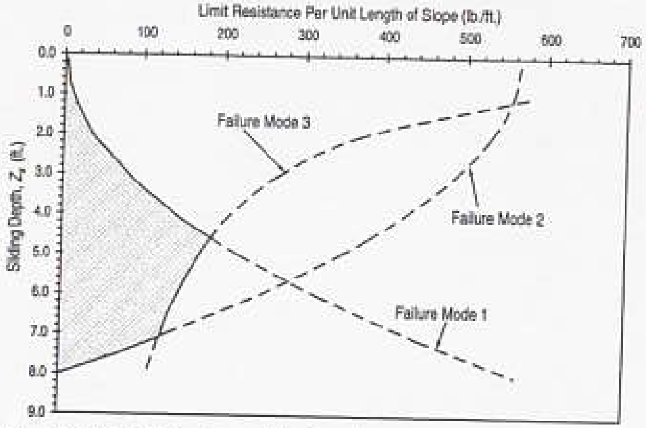

Figure 4 Typical distributions of limit resistance developed for the three limit states considered.

The limit soil pressure is the pressure that will cause the soil to fail laterally at a particular depth. If it is assumed that this load can be simultaneously mobilized along the length of the reinforcing member above the sliding surface, the total limit resistance based on failure of soil above the sliding surface (mode 1) is obtained by integrating the computed limit soil pressure over the length of reinforcement above the sliding surface as shown in Fig. 5. For stability analysis, this total limit resistance force is assumed to act at the sliding surface (Fig. 5b).

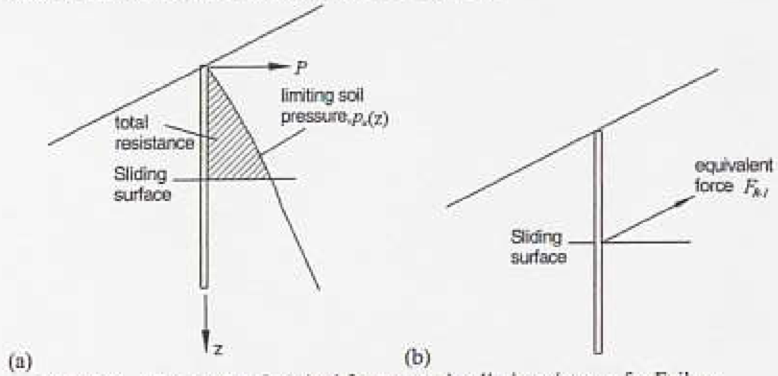

Figure 5 Illustration of method for computing limit resistance for Failure Mode 1: (a) integral of limit soil pressure, and (b) equivalent resisting force.

Since the sliding surface may in general pass through any point on the reinforcing member, additional points on the limit resistance curve are computed by repeating the integration for different sliding depths to establish a complete limit resistance curve describing the total resistance for failure mode 1 as a function of sliding depth as shown in Fig. 4. For failure mode 1, the total resistance increases from a minimum value at the ground surface to a maximum value at the tip of the member. Since stability analyses are generally performed for cross-sections of unit width, the total resisting forces computed by integrating the limit soil pressure are divided by the longitudinal spacing to produce values of the limit force per unit width suitable for stability analyses.

Failure Mode 2 – Limit Anchorage Resistance

The second limit state considered is the one in which reinforcing members have insufficient anchorage length beyond the sliding surface to provide passive resistance that is equal to or greater than that provided by the soil above the sliding surface. If passive failure of the soil below the sliding surface is assumed to be governed by the same limit soil pressure (p_u) as used for failure mode 1, a similar procedure can be used to calculate the limit anchorage resistance.

The resisting force provided by the length of the reinforcing element extending below the sliding surface is obtained by integrating the limit soil pressure (p_u) over the length of the member extending from the sliding surface to the tip of the member as shown by the shaded zone in Fig. 6. It is again assumed that the full limit soil pressure can be mobilized over the entire length of reinforcing member below the sliding surface. The total resistance for a particular sliding depth is again replaced with an equivalent force for stability analysis (Fig. 6b) and the complete limit resistance distribution for the anchorage limit state is calculated by computing the total resisting force for different sliding depths (Fig. 4). As shown in Fig. 4, the limit resistance for failure mode 2 increases from zero for a sliding surface passing through the lower end of the member to a maximum for very shallow sliding surfaces.

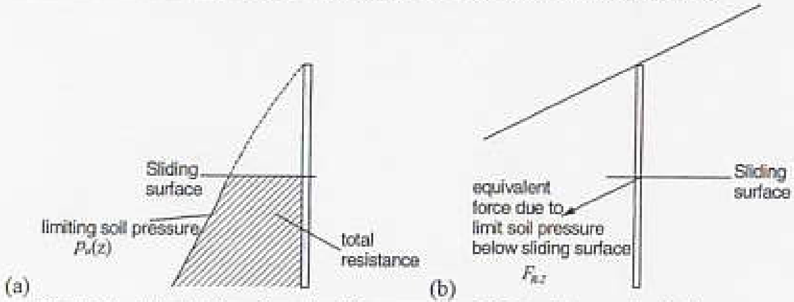

Figure 6 Illustration of method for computing limit resistance for Failure Mode 2: (a) integral of limit soil pressure, and (b) equivalent total resisting force.

Failure Mode 3 – Limit Member Resistance

For conventional structural members, it is often possible to design the members to resist the bending moments and shear forces imposed by the soil, particularly for shallow slides. For recycled plastic members, however, this is generally not possible. It is therefore imperative that structural failure of reinforcing members in bending or shear be considered since application of the predicted limit lateral soil pressures used for development of the previous limit resistance curves may lead to bending moments or shear forces that exceed the capacity of the reinforcing member. In this case, the member will fail prior to the limit soil pressures being fully mobilized and the stabilizing forces predicted by considering failure of the soil alone will be unconservative if the critical sliding surface passes through the portion of the member where structural capacity controls the resistance.

The approach used to account for the potential of the reinforcing member to fail structurally is to consider a factored lateral soil pressure of the form

$$p'(z) = \alpha\, p_u(z) \qquad (1)$$

where $p'(z)$ is a factored pressure and $p_u(z)$ is the limit soil pressure. The unknown factor α is the factor that will produce a distribution of shear or moment such that the maximum shear or moment just equals the shear or moment capacity of the reinforcing member, respectively. To establish the magnitude of α for a particular sliding depth, elastic analyses are first performed to establish the distribution of shear and moment in the member when subjected to the limit soil pressures either above or below the sliding surface. Considering moments, α is then approximated as

$$\alpha = \frac{M_{ult}}{M_{max}} \qquad (2)$$

where M_{max} is the maximum moment determined from elastic analyses and M_{ult} is the moment capacity of the member. While Eq. 2 is strictly an approximation, results of analyses performed to date indicate that it produces acceptably precise values for α. The factor is then applied to the limit soil pressures (Eq. 1) to determine the factored pressures to avoid structural failure of the reinforcing member in bending and the limit resistance is computed using the factored pressure distribution in a manner similar to that used for the other limit states considered (Figs. 5 and 6). Since the distribution of moment, and the maximum moment, are functions of the sliding depth, the factor α must also be a function of the sliding depth so the process is repeated for different sliding depths to develop a limit resistance curve for failure mode 3 as shown in Fig. 4. A similar approach is used to consider shear. However, moments have proven to be the controlling factor for recycled plastic members in all work to date. Additional details regarding calculation of α are provided in Loehr and Bowders (2003).

Once the limit resistance curves for each failure mode are established (Fig. 4), a "composite" limit resistance curve that accounts for all of the failure modes is obtained by taking the least of the three resistance at each sliding depth as shown in Figure 7. This composite curve is then input into conventional slope stability analysis software to determine the factor of safety for a reinforced slope.

DISCUSSION

As shown in Fig. 7, the limit resistance is generally controlled by failure modes 1 and 2, which are controlled by the soil, for sliding surfaces that pass through the upper and lower portions of the reinforcing members. Only over the middle portion of the member does the capacity of the reinforcing member control (mode 3) the limit resistance. Thus, the capacity of the reinforcing members only affects the computed factors of safety when the critical sliding surface passes through the middle portion of the reinforcing members. This is demonstrated in Fig. 8, which shows results of stability analyses for an embankment reinforced with recycled plastic and "strong" reinforcing members (members with sufficient capacity to resist the forces imposed by the soil). As shown in the figure, the factors of safety for both recycled plastic and strong reinforcing members are almost identical in most cases. In cases where the critical sliding surface passes through the middle portion of the reinforcing members, factors of safety for the plastic reinforcement are slightly lower than for "strong" members. However, the difference is less than about 5 percent.

Several issues associated with design of stabilization schemes using recycled plastic reinforcement remain to be addressed. Several of these issues include:

- consideration of the inclination of reinforcing members
- possible contributions from axial forces in the members

- consideration of group effects
- uncertainty in the limit soil pressure
- uncertainly in the calculated maximum moments

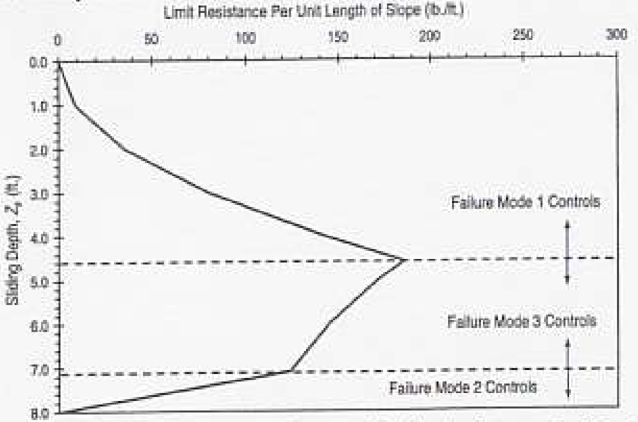

Figure 7 Composite limit lateral resistance distribution for recycled plastic reinforcing member.

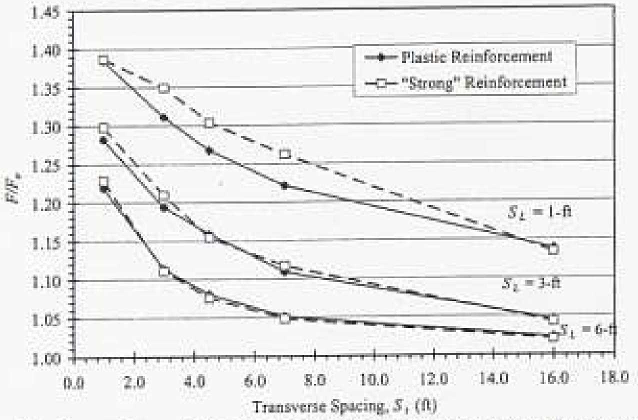

Figure 8 Comparison of factors of safety for recycled plastic and "strong" reinforcing members.

The design method described in this paper has been used to design stabilization schemes using recycled plastic members at five different field test sites. Costs to stabilize the slopes at the field test sites have varied from approximately $4.50 per square foot of slope face for members placed on 3-ft centers to approximately $1.00 per square foot of slope face for members place on 6-ft centers. To date, each of these sites is performing well and evidence from field instrumentation suggests that the design method is at least conservative. This observation is based on the fact that deformations in all test sections have been small despite having low computed factors of safety and that mobilized bending moments in the reinforcing members remain well below the bending capacity of the members. Efforts are ongoing to "calibrate" the design procedure using the available field evidence from these sites to produce a method that more accurately represents the stability of the field sites.

SUMMARY

A design procedure developed to predict the stability of slopes reinforced with recycled plastic reinforcing members has been described. The method uses a limit state design approach to predict the resistance provided by individual reinforcing members. Limit states considered include failure of the soil above or below potential sliding surfaces as well as structural failure of the reinforcing member. Results of analyses using the method indicate that the reduced capacity of recycled plastic reinforcement has only a limited effect on computed factors of safety as compared to factors of safety for "strong" members. Evidence from five field test sites indicates that the method may be conservative so efforts are underway to calibrate the method based on available field evidence.

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