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Kapil Ohri
JP Nagar, Jalandhar, Punjab, India

Dr. Pradeep Kumar
Harcourt Butler Technological, Institute, Kanpur, Uttar Pradesh, India

Correspondence
Kapil Ohri
Vill & P.O. Daburji, Dist. Kapurthala, Punjab, India

Geosynthetics for soil reinforcement -numerical analysis on the effects of prestressing geosynthetics to enhance their reinforcement effect

Kapil Ohri and Dr. Pradeep Kumar

Abstract
This article introduces geosynthetic materials and briefly describes their types and manufacture, functions and applications, properties and tests, design, selection, and specifications. Geosynthetics for soil reinforcement are then discussed in some detail, with specific applications to embankments on soft foundations, steep slopes, and for the backfills of retaining walls and abutments. Emphasis is on the materials properties of the geosynthetics required for design and construction.
Failures of road embankments on discontinuous permafrost commonly occur during thawing of the foundation soil. As an approximation, weak zones created by thawing of discontinuous permafrost can be considered as 'voids' within the foundation. Geosynthetic reinforcements have been used to bridge these 'voids' and provide support to the embankment fill. This paper presents results of a numerical investigation on the effects of prestressing geosynthetics to enhance their reinforcement effect, and thus reduce deformations of embankments over discontinuous permafrost. The study used the commercially available computer program, FLAC. Numerical analysis illustrates that prestressing geosynthetic reinforcement can be effective in controlling deformations and reducing the possibility of collapse of road embankments on degrading discontinuous permafrost.

Keywords: Reinforced Embankment, Geosynthetic Reinforcement, Discontinuous Permafrost, Numerical Modelling, Pretensioning

1. Introduction
Historically, major developments in structural engineering have only been possible because of parallel developments in the technology of construction materials. Larger and more elaborate structures became possible as we went from using wood to building stone to concrete to reinforced concrete and most recently to prestressed reinforced concrete. The development of steel enabled the construction of longer span bridges and taller buildings than were possible using wrought iron or other traditional construction materials. Because the materials of geotechnical engineering are soil and rock, it is difficult to think of similar parallel developments in geotechnical construction and earthen materials in our field. Compaction and other soil improvement techniques occurred largely because of developments in construction equipment by manufacturers and contractors. Probably the best example of a parallel development between material and the construction application is soil reinforcement. In a direct analogy with reinforced concrete, steel and polymeric materials provide tensile resistance and stability to soils that have low to no tensile strength.
Polymeric reinforcement materials are a subset of a much larger recent development in civil engineering materials: geosynthetics. Geosynthetics are planar products manufactured from polymeric materials (the synthetic) used with soil, rock, or other geotechnical-related material (the geo) as part of a civil engineering project or system.
There are few developments that have had such a rapid growth and strong influence on so many aspects of civil engineering practice as geosynthetics. In 1970, there were only five or six geosynthetics available, while today more than 600 different geosynthetic products are sold throughout the world. The size of the market, both in terms of square meters produced and their value, is indicative of their influence. Worldwide annual consumption of geosynthetics is close to 1000 million m2, and the value of these materials is probably close

to US$1500 million. Since the total cost of the construction is at least four or five times the cost of the geosynthetic itself, the impact of these materials on civil engineering construction is very large indeed.
In less than 30 yr, geosynthetics have revolutionized many aspects of our practice, and in some applications they have entirely replaced the traditional construction material. In many cases, the use of a geosynthetic can significantly increase the safety factor, improve performance, and reduce costs in comparison with conventional design and construction alternates.
The first part of this paper is an introduction to geosynthetic materials; included are brief descriptions of their types and manufacture, functions and applications, properties and tests, design, selection, and specifications. The second part deals with the use of geosynthetics for soil reinforcement, with specific applications to embankments on soft foundations, steep slopes, and retaining walls and abutments.

2. Definitions, types, manufacture, and identification

2.1 Definitions and Types

ASTM has defined a geosynthetic as a planar product manufactured from a polymeric material used with soil, rock, earth, or other geotechnical-related material as an integral part of a civil engineering project, structure, or system. A geotextile is a permeable geosynthetic made of textile materials. Geogrids are primarily used for reinforcement; they are formed by a regular network of tensile elements with apertures of sufficient size to interlock with surrounding fill material. Geomembranes are low-permeability geosynthetics used as fluid barriers. Geotextiles and related products such as nets and grids can be combined with geomembranes and other synthetics to take advantage of the best attributes of each component. These products are called geocomposites, and they may be composites of geotextile-geonets, geotextile-geogrids, geotextile-geomembranes, geomembrane-geonets, geotextile-polymeric cores, and even three-dimensional polymeric cell structures. There is almost no limit to the variety of geocomposites that are possible and useful. The general generic term encompassing all these materials is geosynthetic.

2.2 Types and Manufacture

Most geosynthetics are made from synthetic polymers such as polypropylene, polyester, polyethylene, polyamide, PVC, etc. These materials are highly resistant to biological and chemical degradation. Natural fibers such as cotton, jute, bamboo, etc., could be used as geotextiles and geogrids, especially for temporary applications, but with few exceptions they have not been promoted or researched as widely as polymeric geosynthetics.
In manufacturing geotextiles, elements such as fibers or yarns are combined into planar textile structures. The fibers can be continuous filaments, which are very long thin strands of a polymer, or staple fibers, which are short filaments, typically 20 to 100 mm long. The fibers may also be produced by slitting an extruded plastic sheet or film to form thin flat tapes. In both filaments and slit films, the extrusion or drawing process elongates the polymers in the direction of the draw and increases the fiber strength.
Geotextile type is determined by the method used to combine the filaments or tapes into the planar textile structure. The vast majority of geotextiles are either woven or nonwoven. Woven geotextiles are made of monofilament, multifilament, or fibrillated yarns, or of slit films and tapes. Although the weaving process is very old, nonwoven textile manufacture is a modem industrial development. Synthetic polymer fibers or filaments are continuously extruded and spun, blown or otherwise laid onto a moving belt. Then the mass of filaments or fibers are either needlepunched, in which the filaments are mechanically entangled by a series of small needles, or heat bonded, in which the fibers are welded together by heat and/or pressure at their points of contact in the nonwoven mass.
Stiff geogrids with integral junctions are manufactured by extruding and orienting sheets of polyolefins. Flexible geogrids are made of polyester yarns joined at the crossover points by knitting or weaving, and coated with a polymer. For additional details on the composition, materials, and manufacturing of geosynthetics, see.

2.3 Identification

Geosynthetics are generically identified by: (1) polymer; (2) type of fiber or yarn, if appropriate; (3) type of geosynthetic; (4) mass per unit area or thickness, if appropriate; and (5) any additional information or physical properties necessary to describe the material. Four examples are:

- Polypropylene staple fiber needlepunched nonwoven, 350 g/m2;
- Polyethylene net, 440 g/m2 with 8 mm openings;
- Polypropylene biaxial geogrid with 25 mm x 25 mm openings; and
- High-density polyethylene geomembrane, 1.5 mm thick.

3. Functions and applications

Geosynthetics have six primary functions:
1. Filtration
2. Drainage
3. Separation
4. Reinforcement
5. Fluid barrier, and
6. Protection

Geosynthetic applications are usually defined by their primary, or principal, function. In a number of applications, in addition to the primary function, geosynthetics usually perform one or more secondary functions. It is important to consider both the primary and secondary functions in the design computations and specifications.
More than 150 separate applications of geosynthetics have been identified. A few examples follow:
Geotextile filters replace graded granular filters in trench drains to prevent soils from migrating into drainage aggregate or pipes. They are also used as filters below riprap and other armor materials in coastal and river bank protection systems. Geotextiles and geocomposites can also be used as drains, by allowing water to drain from or through soils of lower permeability. Examples include pavement edge drains, slope interceptor drains, and abutments and retaining wall drains.
Geotextiles are often used as separators to prevent fine-grained subgrade soils from being pumped into permeable, granular road bases and to prevent road base materials from penetrating into the underlying soft subgrade. Separators maintain the design thickness and roadway integrity.

Geogrid and geotextile reinforcement enables embankments to be constructed over very soft foundations. They are also used to construct stable slopes at much steeper angles than would otherwise be possible. Polymeric reinforced backfills for retaining walls and abutments was mentioned in the Introduction.

Geomembranes, thin-film geotextile composites, geosynthetic-clay liners, and field-coated geotextiles are used as fluid barriers to impede the flow of a liquid or gas from one location to another. This geosynthetic function has application in asphalt pavement overlays, encapsulation of swelling soils, and waste containment. In the sixth function, protection, the geosynthetic acts as a stress relief layer. A protective cushion of nonwoven geotextiles is often used to prevent puncture of geomembranes (by reducing point stresses) from stones in the adjacent soil or drainage aggregate during installation and while in service.

4. Design and selection

In the early days where there were only a few geotextiles available, design was mostly by trial and error and product selection was primarily by type or brand name. Today, however, with such a wide variety of geosynthetics available, this approach is inappropriate. The recommended approach for designing, selecting, and specifying geosynthetics is no different than what is commonly practiced in any geotechnical engineering design. First, the design should be made without geosynthetics to see if they really are needed. If conventional solutions are impractical or uneconomical, then design calculations using reasonable engineering estimates of the required geosynthetic properties are carried out. Next, generic or performance type specifications are written so that the most appropriate and economical geosynthetic is selected, consistent with the properties required for its design functions, ability to survive construction, and its durability. In addition to conventional soils and materials testing, testing and properties evaluation of the geosynthetic is necessary.

Therefore, careful field inspection during construction is essential for a successful project. Additional discussion on all these points is given by.

5. Geosynthetics properties and tests

5.1 Introduction

Because of the wide variety of products available, with different polymers, filaments, weaving patterns or bonding mechanisms, thickness, mass, etc., geosynthetics have a considerable range of physical and mechanical properties. A further complicating factor is the variability of some properties, even within the same manufactured lot or roll; also, some differences may be due to the test procedures themselves.

Thus, determination of the design properties is not necessarily easy, although geosynthetic testing has progressed significantly in the past 20 yr. Standard procedures for testing geosynthetics have been developed by ASTM and other standards development organizations throughout the world, particularly in Europe, Japan, and Australia. The design properties required for a design will depend on the specific application and the associated function(s) the geosynthetic is supposed to provide.

Geosynthetic properties can be classified as (1) general, (2) index, and (3) performance properties. See for a listing of the various properties under these categories, while describe test methods for the various geosynthetics properties, including those appropriate for geomembranes and other products used for waste containment.

5.2 General and Index Properties and Tests

General properties include the polymer, mass per unit area, thickness, roll dimensions and weight, specific gravity, etc. Index tests do not give an actual design property in most cases, but they do provide a qualitative assessment of the property of interest. When determined using standard test procedures, index test values can be used for product comparison, specifications, quality control purposes, and as an indicator of how the product might survive the construction process. These latter properties are called constructability or survivability properties. Index tests include uniaxial mechanical strength (grab tensile; load-strain; creep, tear, and seam strength); multiaxial rupture strength (puncture, burst, and cutting resistance; flexibility); endurance or durability tests (abrasion resistance; UV stability; chemical and biological resistance; wet-dry and temperature stability); and hydraulic index tests (apparent opening size, percent open area; pore size distribution; porosity; permeability and permittivity; transmissivity).

5.3 Performance Properties and Tests

Performance properties require testing the geosynthetic and the soil together in order to obtain a direct assessment of the property of interest. Because performance tests should be conducted under design specific conditions and with soil samples from the site, these tests must be performed under the direction of the design engineer. Performance tests are not normally used in specifications; rather, geosynthetics should be preselected for performance testing based on index values, or performance test results should be correlated to index values for use in specifications. Examples of performance tests include in-soil stress-strain, creep, friction/adhesion, and dynamic tests; puncture; chemical resistance; and filtration or clogging resistance tests.

6. Specifications

Good specifications are essential for the success of any civil engineering project, and this is especially true for projects in which geosynthetics are to be used. Give guidance on writing generic and performance-based geotextile specifications. Specifications should be based on the specific geosynthetic properties required for design, installation, and long-term performance. To specify a particular brand name of a geosynthetic or its equivalent can cause difficulties during installation. The contractor may select a product that has completely different properties than intended by the designer, and determination of what is "equivalent" is always a problem.

All geosynthetic specifications should include:

- General requirements
- Specific geosynthetic properties
- Seams and overlaps
- Placement procedures
- Repairs, and
- Acceptance and rejection criteria

General requirements include the types of geosynthetics, acceptable polymeric materials, and comments related to the stability of the material. Geosynthetic manufacturers and representatives are good sources of information on these characteristics. Other items that should be specified in this section are instructions on storage and handling so products can be protected from exposure to ultraviolet light, dust, mud, or anything that may affect its performance. If pertinent, roll weight and dimensions may also be specified, and certification requirements should be included in this section.

Specific geosynthetic physical, index, and performance properties as required by the design must be listed. Properties should be given in terms of minimum (or maximum) average roll values (MARV) and the required test methods. MARVs are the smallest (or largest) anticipated average value that would be obtained for any roll tested. This average property value must exceed the minimum (or be less than the maximum) value specified for that property based on a particular test. Ordinarily it is possible to obtain a manufacturer's certification for MARVs.

Approved products lists can also be developed based on laboratory testing and experience with specific applications and conditions. Once an approved list has been established by an agency, new geosynthetics can be added after appropriate evaluation. Development of an approved list takes considerable initial effort, but once established, it provides a simple and convenient method of specifying geosynthetics.

In virtually all geosynthetics applications, seams or overlaps are required and must be clearly specified. A minimum overlap of 0.3 m is recommended for all geotextile applications, but overlaps may be increased due to specific site and construction requirements. If overlaps will not work, then the geosynthetics must be seamed.

Geotextiles are commonly seamed by sewing; see for details. The specified seam strengths should equal the required strength of the geosynthetic, in the direction perpendicular to the seam length and using the same test procedures. Seam strengths should not be specified as a percent of the geosynthetic strength. Geogrids and geonets may be connected by mechanical fasteners, though the connection may be either structural or a construction aid (i.e., strength perpendicular to the seam length is not required by design). Geomembranes are thermally or chemically bonded; see for details.

For sewn geotextiles, geomembranes, and structurally connected geogrids, the seaming material (thread, extrudate, or fastener) should consist of polymeric materials that have the same or greater durability as the geosynthetic being seamed. This is true for both factory and field seams.

Placement procedures should be specified in detail and on the construction drawings. These procedures include grading and ground-clearing requirements, aggregate specifications, aggregate lift thickness, and equipment requirements. These requirements are especially important if the geosynthetic was selected on the basis of survivability. Detailed placement procedures are given by.

Repair procedures for damaged sections of geosynthetics (i.e., rips and tears) should be detailed in the specifications. Geosynthetic acceptance and rejection criteria should be clearly and concisely stated in the specifications. All installations should be observed by a competent inspector who is knowledgeable about placement procedures and design requirements. Sampling and testing requirements should also be specified.

7. Numerical analysis

Numerical methods for analyzing geosynthetic-reinforced embankments over voids assume that the soil and reinforcement rest initially on a firm foundation. With the development of a void under the reinforcement, the overlying soil deflects into the void. The deflection mobilizes two support mechanisms - (1) bending of the embankment soil and (2) stretching of the geosynthetic (Giroud *et al*. 1990) [6]. Bending of the embankment soil generates arching effects within the soil above the reinforcement and the load being transferred to the reinforcement over the void is less than the theoretical weight of the overlying soil. Stretching of the geosynthetic mobilizes part of the reinforcement strength and the material begins to act as a tension membrane supporting loads normal to its surface.

Analytical techniques used for design have until recently been based on a limit equilibrium method that uses combined arching and tension membrane theory. This approach uses two main steps in the analysis. First, the behaviour of the embankment soil is analyzed using classical arching theory to calculate the applied vertical pressure on the geosynthetics. Second, the required horizontal geosynthetic tension is determined using tensioned-membrane theory. In this approach, the soil response (arching) was uncoupled from the geosynthetic response (tensioned membrane) to simplify the complex nature of soil-geosynthetic interaction. Uncoupling the two mechanisms in this way means that the strain in the soil required to generate soil arching is compatible with the strain needed to mobilize tension in the reinforcement.

Tensioned membrane theory is based on two assumptions. One assumes that strain in the portion of the geosynthetic overlying the void is uniformly distributed. The second assumes that strain in the portion of the geosynthetic outside the void is zero and, that therefore; this portion does not slide towards the void. Although these two assumptions simplify the analysis, no attempt has been made to verify their validity.

The British Code of Practice, BS 8006 (BSI 1994) does not consider soil arching. Instead, it assumes that the full weight of an assumed wedge that forms above the void is supported by the reinforcement. It further assumes that the load acting on the reinforcement is distributed along the horizontal span of the reinforcement as opposed to being along the deflected length. BS 8006 does not address compatibility issues between the reinforcement and the soil. The calculated reinforcement load is therefore an upper estimate, since soil arching is not considered.

Recently, numerical methods based on continuum mechanics have been used to analyze geosynthetic-reinforced embankments over voids. Poorooshasb (2002) [15] used a numerical technique based on an integro-differential (ID) equation in conjunction with a soil constitutive model to examine the behaviour of a geotextile-reinforced gravel mat bridging a cavity such as one that may be created by a sinkhole. Villard *et al*. (2000) [18] used the finite element method to gain a better understanding of results from full-scale tests of reinforced fill over localized sinkholes. A finite difference computer program, FLAC was used to analyze the behaviour of a reinforced fill over a void (Agaiby and Jones, 1995; Kempton *et al*., 1996) [2, 8]. This finite difference model uses a dynamic relaxation algorithm that is well suited to ill-behaved systems associated with material and geometric non-linearity, large strains, or where physical instability is anticipated. Although FLAC aims at providing static solutions to problems, dynamic equations are included in the mathematical formulations. The procedure first invokes the equation of motion to derive new velocities and displacements for stresses and forces. The strain rates are obtained from the velocities, and then new stresses are derived from the strain rates.

8. Calibration of numerical analysis

The authors have used the current version of the finite difference-based software FLAC, version 4.00 (Itasca, 2002) in their study of highway fills on degrading permafrost. To gain confidence, work began by simulating the problem studied by Agaiby and Jones (1995) [2]. The simulation was done to demonstrate that numerical results in the present study are in general agreement with results obtained by Agaiby and Jones using an earlier version of FLAC.

Figure 1 shows a schematic of the problem studied by Agaiby and Jones. A fill with a thickness, H = 2.0 m was constructed over a rigid formation. The bottom has a fixed boundary, while both sides of the problem have roller boundaries. A void of variable width B was considered to develop suddenly in the lower layer after the fill had been constructed. The void was bridged by geosynthetic reinforcement. A nominal surcharge of 20 kN/m2 was applied on the fill surface to simulate traffic loads. The problem was studied for infinitely long fill, that is, for a plane-strain condition.

Relevant soil properties used by Agaiby and Jones (1995) [2] include: soil density, ρ = 1750 kg/m3, bulk modulus, K = 33.33 MPa, shear modulus, G = 15.37 MPa, cohesion, c' = 0 kPa, and φ' = 34°. The reinforcement was modelled as a series of cable elements that have no flexural rigidity and can only resist tension. Table 1 summarizes the properties used in the modelling for the reinforcement. Additional work has been done using stiffer reinforcement than that done by Agaiby and Jones (1995) [2] Reinforcement R2 in Table 1 has yield strength twice that of reinforcement R1, and stiffness 28% higher than R1. Figure 2 depicts the rotation of the major principal stresses due to arching in the fill. This demonstrates the capability of the numerical modelling to represent the problem being investigated in terms of soil arching and soil-reinforcement interaction.

Figure 3 shows results for the variation of normalized tension in the reinforcement and maximum surface displacements with the width B of the void. For reinforcement R1, which is the same as that used by Agaiby and Jones (1995) [2], the authors' results and the Agaiby-Jones results are the same. For clarity, only the authors' results are shown in the figure.

As mentioned earlier, additional sets of simulations were also performed. One (R2) had higher reinforcement stiffness (Table 1). The second (R1P) had the same reinforcement stiffness as in R1 but the reinforcement was now prestressed. Two parameters are of interest, namely the maximum surface displacement, ys and the maximum mobilized tension of reinforcement expressed as a ratio of yield strength, T/Ty. Figure 3 shows calculated values of ys and T/Ty plotted versus the width of the void for the R1, R2 and R1P simulations.

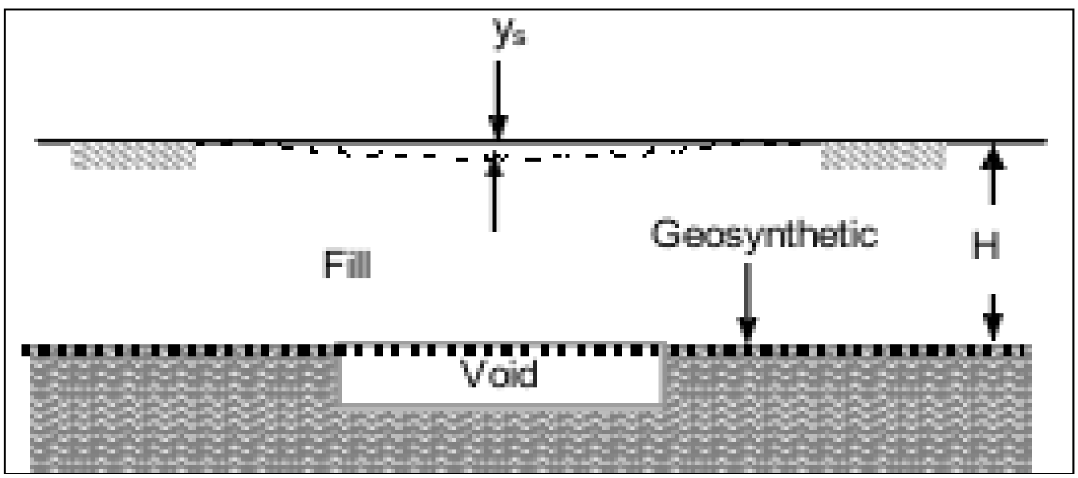

Fig 1: Problem studied by Agaiby and Jones (1995) [2]

Table 1: Geo synthetic reinforcement properties

Reinf.	Young's modulus (GPa)	Area (10^{-3} m^2)	Yield strength(kN/m)
R1*	2.35	1.7	400
R2 †	3.00	1.7	800

* Same reinforcement used by Agaiby and Jones (1995) [2]
† Arbitrary reinforcement

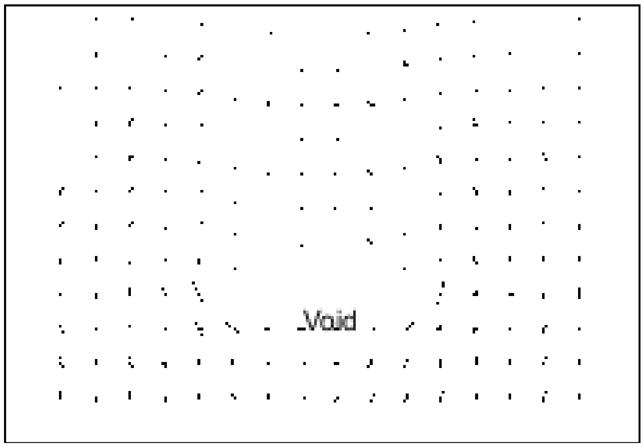

Fig. 2: Rotation of principal stresses due to arching in the fill overlying the void

Comparing the results for the R1 and R2 sets of calculations shows that the maximum surface settlements become smaller as the stiffness of the reinforcement is increased. Also, as the reinforcement becomes stronger, associated values of ys and the normalised tension T/Ty become relatively smaller.

When initiating the research described in this paper, the authors proceeded on the basis that prestressing the reinforcement would enhance the reinforcement effect of geosynthetics and reduce deformations of the soil-reinforcement composite system. The prestressing simulation (RP1) used a prestressing force of 20 kN/m in the reinforcement. (The initial tension represents a value of T/Ty = 0.05). Figure 3 shows that prestressing the weaker of the two reinforcements discussed earlier (R1) significantly increases the mobilized tension and reduces the maximum surface displacements. It is noted that geosynthetic reinforcements available in the market do not necessarily increase much in stiffness with increasing yield strength. This is particularly true at reinforcement strain levels of 5-10%, which are normally the working strain levels observed in most reinforced soil structures.

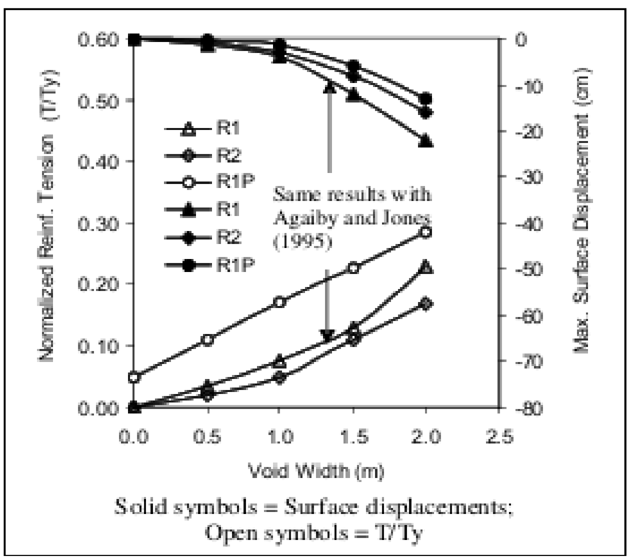

Fig. 3 Maximum surface displacement and mobilized reinforcement tension for different widths of void

9. Conclusion

Results have been presented from numerical analysis of the effects of prestressing geosynthetic reinforcements in embankments over permafrost soils that include rapidly-occurring voids caused by melting ice wedges. Qualitative results from this study illustrate that prestressing geosynthetic reinforcements can be effective in controlling deformations and reducing the possibility of collapse.

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