CONNECTION STRENGTH CRITERIA FOR MSE WALLS

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ABSTRACT

A rational design approach for determining the connection strength for geosynthetic reinforced, mechanically stabilized earth highway walls is presented. This procedure draws heavily on similar procedures established within guidelines for determining the long-term allowable strength of the geosynthetic reinforcement for transportation applications. Test procedures and results of a limited testing program are presented and use of the proposed design methodology demonstrated.

INTRODUCTION

Over the last decade, polymer reinforced soil retaining walls have gained wide acceptance as an economical alternative to both conventional cast-in-place concrete retaining walls and mechanically stabilized earth (MSE) walls using metallic reinforcements. The state-of-practice methodology used to analyze polymer reinforced soil walls has been advanced by Mitchell and Villet, 1987 *(1)*; Christopher et al., 1990 *(2)*; and Task Force 27, 1990, *(3)*. Procedures for both the internal and external stability analysis of reinforced soil walls and for the determination of allowable design tensile loads on geosynthetics are presented in these documents.

However, the connection between the reinforcement and the wall facing is not comprehensively addressed in these guidelines. Task Force 27 *(3)*, which specifically addresses highway wall applications, established the following general criteria for the connection strength of MSE walls using geosynthetic reinforcements:

- Extensible reinforcement connections to the wall face should be designed to carry 100% of the maximum design load at all levels within the wall.

- A representative section of the connection type (e.g., segmental concrete unit and geogrid reinforcement) should be load-tested in order to determine the actual allowable working load for the connection system.

- The allowable design strength of the reinforcement cannot exceed that of the measured connection strength of the facing system.

- The allowable design strength of the connection should be determined at the in-ground service temperature. If no information is provided the assumed temperature shall be taken as 37.8°C.

Application of these general criteria to design of a wall structure is subject to interpretation by the design engineer and by the contracting agency.

Tensile strength computations *(3,4,5,6,7)* for polymer soil reinforcement elements account for creep, damage during installation, biological degradation, and chemical degradation. Intuitively, the connection of reinforcement to wall facing elements should also consider these potential effects. The effects may vary, as interaction mechanisms, placement techniques, and environment may differ between reinforcement placed in a soil and reinforcement placed in a retaining wall face unit. The Task Force 27 guidelines and AASTHO Bridge Manual *(8)* do not specifically state that the factors effecting strength should be addressed separately for the connection areas. Hence, current state-of-practice for the design of highway MSE structures does vary with interpretations by designer and/or regulatory agency, and whether or not the long-term performance of the connection is considered. Short-term connection tests are routinely used to predict long-term performance.

An expanded connection strength design procedure, consistent with existing design guidelines for computation of allowable tensile strength, has been developed and is presented within. The proposed procedure addresses the long-term performance of the connection between the geosynthetic reinforcement and wall face elements. A laboratory testing program has also been conducted to determine the long-term mechanical performance (durability was not within the scope of this test program) of some wall connections. Geogrid soil reinforcement elements and concrete segmental retaining wall (SRW) facing units were specifically examined, at ambient (≈23°C) temperatures. The results of the testing program and an example calculation with the proposed procedure are presented.

ALLOWABLE TENSILE STRENGTH COMPUTATION PROCEDURES

The Task Force 27 guidelines, which are also incorporated into the AASHTO Bridge Manual, established a procedure for the determination of the long-term allowable strength (T_a) of geosynthetic soil reinforcement for MSE highway wall structures. The criteria used in that procedure, with some modifications, appear to be appropriate for the evaluation of the connection strength between the reinforcement and wall facing elements, for transportation related projects.

One design consideration is serviceability. At the design load, how much movement might the wall experience during the life of the structure? This movement will be a function of the polymer reinforcement elongation (material and product structure creep), and possibly creep associated with the soil-reinforcement interaction. After construction of a geosynthetic MSE wall, the total creep of the reinforcement should be limited so that the wall face does not move significantly (i.e., structure remains serviceable) and stays aesthetically pleasing. Thus, per Task Force 27 guidelines (without connection strength and geogrid junction strength criteria shown), the long-term allowable strength must be less than or equal to the following:

Serviceability Criteria

$$T_{as} = \frac{T_w}{FD \times FC} \qquad \text{Equation [1]}$$

where: T_{as} = long-term geosynthetic tension based on a serviceability state criterion

T_w = tension level at which total strain does not exceed 5% within the desired lifetime at the design temperature

FD = factor for chemical and biological durability

FC = factor for construction damage

The Task Force 27 guidelines further establishes that the long-term allowable strength of the geosynthetic must also be evaluated at the limit state, and that failure by rupture of the reinforcement must be prevented. The Equation for this evaluation is:

Limit Sate Criteria

$$T_{al} = \frac{T_l}{FD \times FC \times FS} \qquad \text{Equation [2]}$$

where: T_{al} = long-term geosynthetic tension based upon a limit state criterion

T_l = the highest tension level at which the accumulated creep strain-rate continues to decrease with log-time within the required design lifetime at the design temperature

FS = factor of safety for general uncertainties

The limit state criteria evaluates the allowable strength of the reinforcement by considering creep of the geosynthetic (i.e., from 10,000 hour creep tests on actual samples of the reinforcement and extrapolation to the design life), the effects of installation damage, and durability. Finally, the strength is reduced by a factor of safety for general uncertainties associated with material properties, design and construction. A minimum factor of safety of 1.5 is required in the Task Force 27 guidelines, and is used with full (i.e., unfactored) peak soil shear strength values.

Guidance for quantifying installation damage and durability factors have been provided by the Geosynthetic Research Institute (GRI) *(5,6)* and Task Force 27. After determining serviceability and limit state tension values and the appropriate reduction factors, the long-term allowable strength (T_a) of the geosynthetic reinforcement is established as the minimum of T_{as} or T_{al}, per Equations [1] and [2], respectively. The long-term allowable strength, however, must also consider, and may be limited by, the connection strength between reinforcement and wall face.

Additionally, determination of the coefficient of interaction (C_i) between the reinforcement and soil as determined from pullout tests is limited by a serviceability requirement in the Task Force 27 guidelines. The ultimate pullout capacity of a reinforcement may occur at displacements of 50 to 100 mm. This magnitude of movement could be unacceptable with regard to the alignment of a retaining wall face. Therefore, for embedment in soil, the maximum allowable pullout force used to determine C_i was established at 20 mm limit on pullout. Wall movement associated with tensile loading of the reinforcement within the soil mass is limited both by the 5% serviceability creep strain limit and the 20 mm limit on pullout.

PROPOSED CONNECTION STRENGTH DESIGN PROCEDURE

The design of the connection between the reinforcement and wall face for a geosynthetic reinforced MSE wall, used in transportation applications, should consider the same generalized criteria established by Task Force 27 for evaluation of long-term allowable strength of the soil reinforcement. Both a serviceability and a limit state analysis should be utilized.

Just as strain of the reinforcement and pullout of the reinforcement within the soil mass are limited in determining the T_a of the geosynthetic, the allowable deformation of the geosynthetic at the wall face connection should be limited. The movement of the wall face over the design life may be restricted by limiting the deformation at the connection. Although Task Force 27 guidelines do not specifically address the maximum elongation between reinforcement and wall face, it does limit the amount of overall elongation of the reinforcement embedded in soil during pullout to less than 20 mm. This deformation is as measured with a *quick* (e.g., displacement rate of 1 mm/minute) pullout test. Therefore, for consistency, a 20 mm deformation, as determined with a *quick* connection strength test, is established in this document as the maximum allowable movement at the connection. The allowable *serviceability* connection strength is then determined as follows:

Serviceability Criteria

$$T_{cs} = \frac{T_{wconn}}{FD \times FC} \qquad \text{Equation [3]}$$

where: T_{cs} = long-term allowable connection strength based upon a serviceability criterion

T_{wconn} = connection strength at 20 mm displacement, at the design temperature

FD = factor for durability in the connection environment

FC = factor for installation damage of connection construction

The results of a *quick* connection test between a geosynthetic reinforcement (geogrid of singular manufacture construction) and a concrete SRW unit that utilizes a pinned type of connection, are shown in Figure 1. The ultimate connection strength, T_{ult} is equal to 47.5 kN/m for this particular test, and occurs at a total deformation of 90 mm. However, for serviceability requirements (i.e., the connection strength at 20 mm displacement) T_{wconn} is equal to 25.4 kN/m.

The allowable connection strength, at a limited displacement, can be calculated with Equation 3. This criteria is intended as a guideline such that post-construction movement of the wall face, if any occurs, is limited to an acceptable level.

The ultimate strength of the connection must also be evaluated. The allowable limit state connection strength is determined as follows:

Limit State Criteria

$$T_{cl} = \frac{T_{lconn} \times R_D}{FD \times FC \times FS} \qquad \text{Equation [4]}$$

where: T_{cl} = long-term allowable connection strength based upon a limit state criterion

T_{lconn} = creep limited strength of the connection, at the design temperature.

R_D = reduction factor

FS = factor of safety for general uncertainties

The creep limited strength should be determined from creep tests of representative connections. These tests should be performed in general accordance with GRI Test Method GG5 - Geogrid Pullout *(9)* for a minimum test duration of 1,000 hours. This minimum time is recommended by the authors, and is consistent with connection or seam strength criteria as set forth in GRI Standards of Practice *(5,6)*. This duration appears acceptable if the rate of creep at termination of the test is approximately equal to that derived from creep testing of the geosynthetic itself. If not, the test duration should be extended. In no case should the value of the creep limited strength of the connection be larger than the creep limited strength of the geosynthetic.

The factor for installation damage may be quantified by constructing the connection, compacting the unit fill, and applying a surcharge pressure to the units. After applying the desired normal pressure the reinforcement is exhumed. The ultimate strength of the reinforcement after installation is then determined and compared to the ultimate strength of the undamaged reinforcement to compute a factor for installation damage. The factor, FC, can be quantified. However, full-scale laboratory tests on representative connections directly incorporate the effect of damage into the force-displacement and force-time response curves.

The factor, FD, should address possible degradation of the soil reinforcement element in the connection environment (e.g., placed between SRW units and exposed to draining water; cast into concrete; etc.). Both potential chemical and biological degradation must be addressed. Degradation of all components of a geosynthetic reinforcement element (e.g., coating and core of reinforcements of composite construction) must be considered. The effects of potential degradation on connection strength (e.g., decrease in reinforcement tensile strength; decrease in frictional interlock with face units) should be evaluated.

A reduction factor (R_D) at the connection should also be determined or estimated. The Task Force 27 guidelines require that the connections of geosynthetic reinforcements be designed to carry 100% of the maximum design load at all levels of reinforcement within the wall. A reduction factor of 1.0 meets this requirement. However, tensile load in the reinforcement at the wall face may not reach the maximum reinforcement design load, and may be only some portion of the ultimate design load for any layer *(2)*. Thus, use of a R_D value less than one may be appropriate. However, unless field-instrumented walls with specific reinforcement and wall face type can substantiate using a lower factor of safety, $R_D = 1.0$ is recommended by the authors. Finally, the strength is reduced by a factor of safety for general uncertainties. A factor of safety of 1.5 is consistent with the safety factor used with the Task Force 27 limit state criterion.

The determination of the allowable design strength (T_d) of the reinforcement is, therefore, limited by Equations 1 through 4 and is the least of the four. The connection strength will typically be a function of normal pressure. Thus T_d will likely vary with depth below top of wall, and with batter of SRW units *(10)*. At any given elevation, T_d is equal to the lowest of:

$$T_d \leq T_{as} = \frac{T_w}{FD \times FC} \qquad \text{Equation [1]}$$

$$T_d \leq T_{al} = \frac{T_l}{FD \times FC \times FS} \qquad \text{Equation [2]}$$

$$T_d \leq T_{cs} = \frac{T_{wconn}}{FD \times FC} \qquad \text{Equation [3]}$$

$$T_d \leq T_{cl} = \frac{T_{lconn} \times R_D}{FD \times FC \times FS} \qquad \text{Equation [4]}$$

TEST PROGRAM

A laboratory testing program was developed to evaluate the connection strength factors T_{wconn}, T_{lconn} and FC of a geosynthetic reinforcement to a SRW unit. The testing program specifically evaluated geogrids with a single, pinned type SRW unit. The first phase of the connection strength test program was to evaluate the connection strength at 20 mm deformation and the ultimate connection strength with *quick* tests. The second phase of the program involved the quantification of the factor of safety for installation damage, *FC.* The final phase, involved the determination of the creep limited strength of the connection.

The connection strength tests for Phases I and III of the program were performed in general accordance with the GRI Test Method GG5 - Geogrid Pullout, with modifications to the test procedures for use with the SRW units. The connection strength tests were conducted in a pullout test box that is 0.9 m wide, 2.1 m long, and 0.5 m deep.

The configuration for each connection strength test is presented conceptually in Figure 2. The reinforcement was placed between two layers of SRW units. The geogrid reinforcement was placed over the connecting pins and pulled taut to the pins prior to placing the second row of SRW units. The SRW units were stacked in a running bond configuration. The voids in and around the units were filled with crushed stone (#57 stone), which met the "select backfill" requirements outlined in Task Force 27.

The specific details regarding the connection strength testing for each phase of the test program are summarized below.

- Text Box Dimensions: 0.9 m by 2.1 m.
- Text Box Height: 0.25 m above and below the pullout specimen for a total height of 0.5 m.
- Normal stress applied using an air bladder to the SRW/gravel/geogrid system in the box.
- Soil Placement: compacted into all block apertures and areas surrounding blocks by hand tamping to approximately 90 percent relative density under dry conditions.

- For each pullout test, fresh epoxy encapsulated geogrid samples were secured to a clamping device. This ensured consistent load distribution over the width of the test specimen during pullout tests.
- Displacement of the reinforcement was measured from the back of the SRW units.
- Typical reinforcement widths for the tests were 0.8 m.

For Phase I:

- All tests were run until a constant or decreasing pullout load was recorded. Hydraulic ram displacement rate: 1 mm/minute, as measured on the specimen clamp.

For Phase II:

- SRW unit to geogrid connections were constructed within the pullout box. A normal pressure was applied.
- Geogrid samples were exhumed and wide width tensile tests were run to quantify *FC*.

For Phase III:

- For all geogrids evaluated in this test program the in-isolation creep limited strength of the geogrid (i.e., T_l of Equation 2) was selected as the long-term (1,000 hour) constant load. Depending on the geogrid tested this load represented between 60% and 80% of the ultimate connection strength based on the Phase I tests.

A series of connection strength tests using the procedures outlined above were performed on several different geogrids (Table 1). The various confining pressures used in testing are listed in Table 2. A single test for a particular geogrid was performed at the noted confined pressure.

TEST RESULTS

The connection force at 20 mm horizontal displacement and the peak value of connection force for the thirteen pullout tests conducted under Phase I of the program are presented in Table 2. A typical plot of applied connection force versus horizontal displacement for a *quick* tests is shown in Figure 1.

The results of Phase II of the test program, quantification of the factor for construction installation damage, are 1.08 for Geogrid A, 1.02 for Geogrid B, and 1.01 for Geogrid C. Typical results of wide width testing for are shown in Figure 3. The tensile force versus strain curves comparing undamaged and damaged geogrid (Figure 3) is in agreement with the findings of other researchers *(Allen, (14))*, that construction damage does not effect measured strains at loads below failure.

The results from the Phase III portion of the test program for geogrid B are presented graphically in Figure 4 (total displacement vs log-time plot). The total displacement even under long-term sustained loading conditions is below the 20 mm serviceability requirement established from the *quick* tests. A plot of average (of 3 points within the embedded area) strain of the geogrid at the connection versus log time is also shown in Figure 4. This response is consistent with in-isolation creep test response of the geogrid. The creep limited strength of the connections based on the results of the Phase III test program are 20.4, 33.6 and 43.8 kN/m for geogrids A, B, and C respectively.

The results presented in Tables 2 and the above paragraphs can now be used to determine the connection strength for the particular materials tested. For example, the connection strength for Geogrid B at a confining pressure of 69 kN/m^2 is determined as follows:

Serviceability

$$T_{cs} = \frac{T_{wconn}}{FD \times FC} = \frac{25.4}{1.1 \times 1} = 23kN / m$$

Limit State

$$T_{cl} = \frac{T_{lconn} \times R_D}{FD \times FC \times FS} = \frac{33.6 \times 1}{1.1 \times 1 \times 1.5} = 20kN / m$$

Note that the minimum value of *FD* allowed by Task Force 27 (i.e., *FD* = 1.1) was used in this example, as the determination of *FD* is beyond the scope of this study. Values of *FC* equal to 1 were used in the computations as full-scale laboratory test results directly include the effects of construction damage. The allowable connection strength is the lower of these and therefore, is equal to 20 kN/m. This value can then be compared to the long-term allowable geogrid strength, and the lower value used for design purposes.

CONCLUSIONS

The required, or design, connection strength between the geosynthetic reinforcement and wall face elements in transportation MSE walls is not clearly defined in existing guidelines. Traditionally, connections have been designed using *quick* testing and safety factors per the designer's judgment or agency guidelines. Displacements and/or deformations of the wall face over time have been assumed to be acceptable. This paper presents a design rationale that accounts for both serviceability and limit state criteria for use in design of geosynthetic reinforced MSE walls. This proposed design method is specifically intended for use in transportation projects, as it is based upon and is consistent with existing transportation guidelines *(1,2,3,7,8)*.

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TABLE 1 - PROPERTIES OF GEOGRIDS TESTED[1]

Property	Geogrid "A"	Geogrid "B"	Geogrid "C"	Geogrid "D"
Manufacture	Singular	Singular	Singular	Singular
Polymer Composition	Polyethylene	Polyethylene	Polyethylene	Polyethylene
Junction Method	Planar	Planar	Planar	Planar
Aperture Size, mm				
Longitudinal	145	145	145	145
Transverse	17	17	17	17
Thickness, mm				
at rib	0.8	1.3	1.8	1.3
at junction	2.8	4.3	5.8	4.1
Wide Width Strip Tensile, (ASTM D4595), kN/m				
2% strain	14.6	29.2	38.0	5.4
5% strain	24.8	52.4	60.0	10.2
ultimate	54.0	86.0	116.8	17.5

[1] Values from *(11,12)*

TABLE 2 - SUMMARY OF CONNECTION STRENGTH TEST RESULTS FOR PHASE I OF THE TESTING PROGRAM

(from *(13)*)

GEOGRID	NORMAL STRESS (kN/m^2)	CONNECTION STRENGTH @ 20 mm DISPLACEMENT (kN/m)	PEAK CONNECTION STRENGTH (kN/m)
Geogrid A	28	13.0	27.2
	48	11.5	32.7
	69	15.2	33.7
Geogrid B	28	17.5	35.4
	48	18.6	39.8
	69	25.4	47.5
	103	25.8	56.9
Geogrid C	48	26.2	50.1
	69 10 psi	29.7	53.4
	103	27.7	56.9
Geogrid D	14	17.3	21.9
	28	18.3	21.2
	42	17.8	21.2

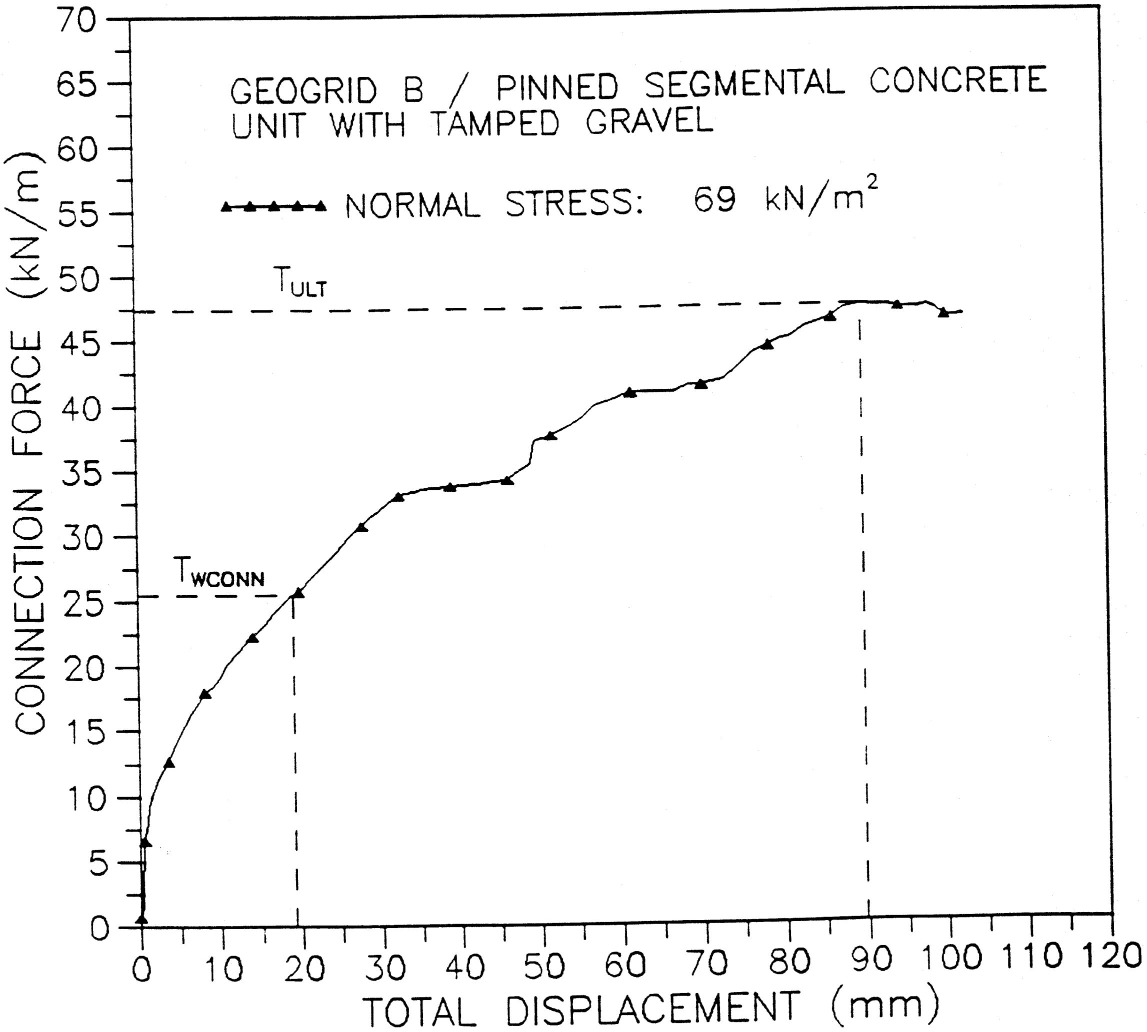

FIGURE 1. QUICK CONNECTION TEST RESULTS FOR A GEOGRID CONCRETE SRW UNIT

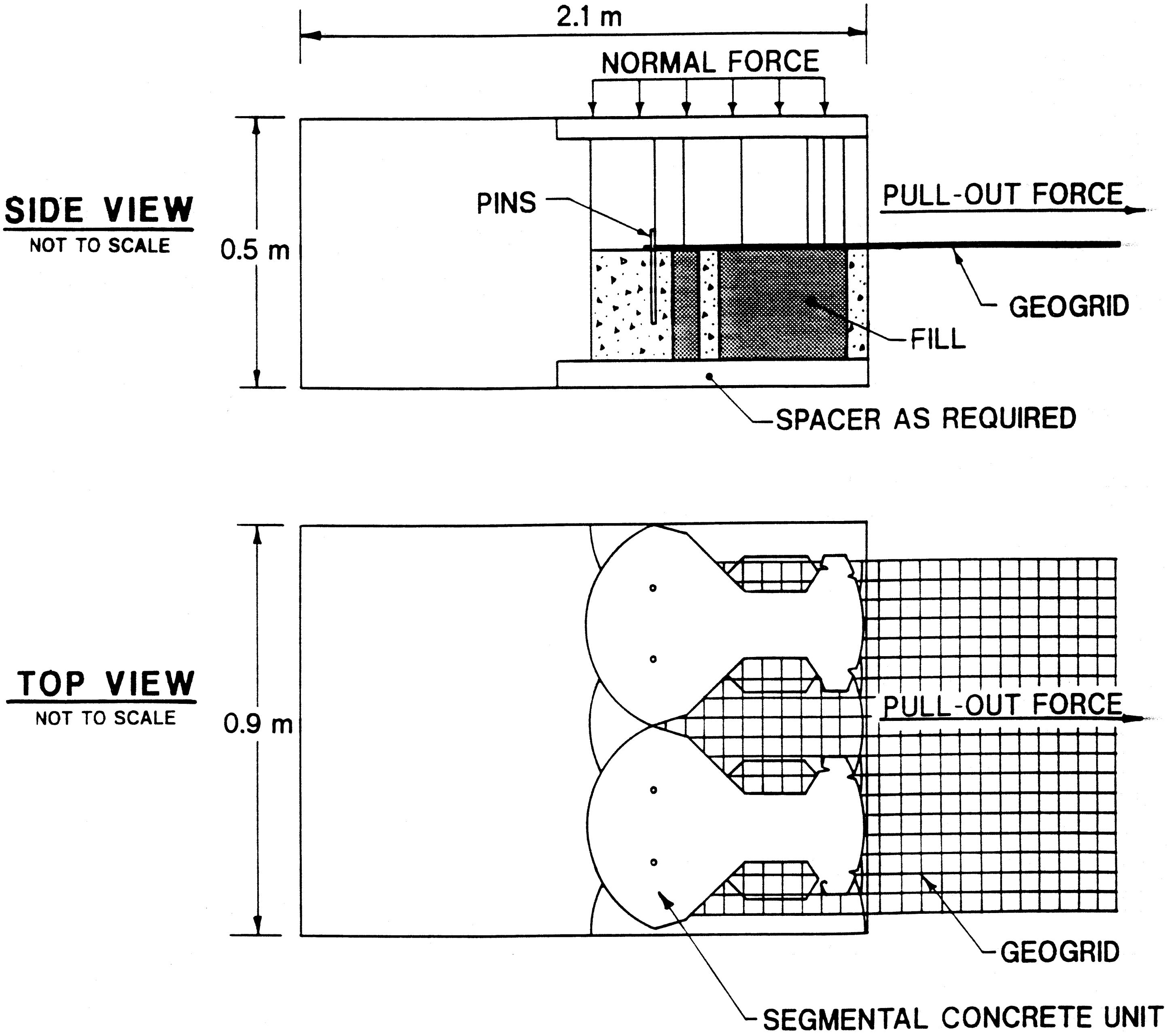

FIGURE 2. SCHEMATIC CONNECTION TEST CONFIGURATION

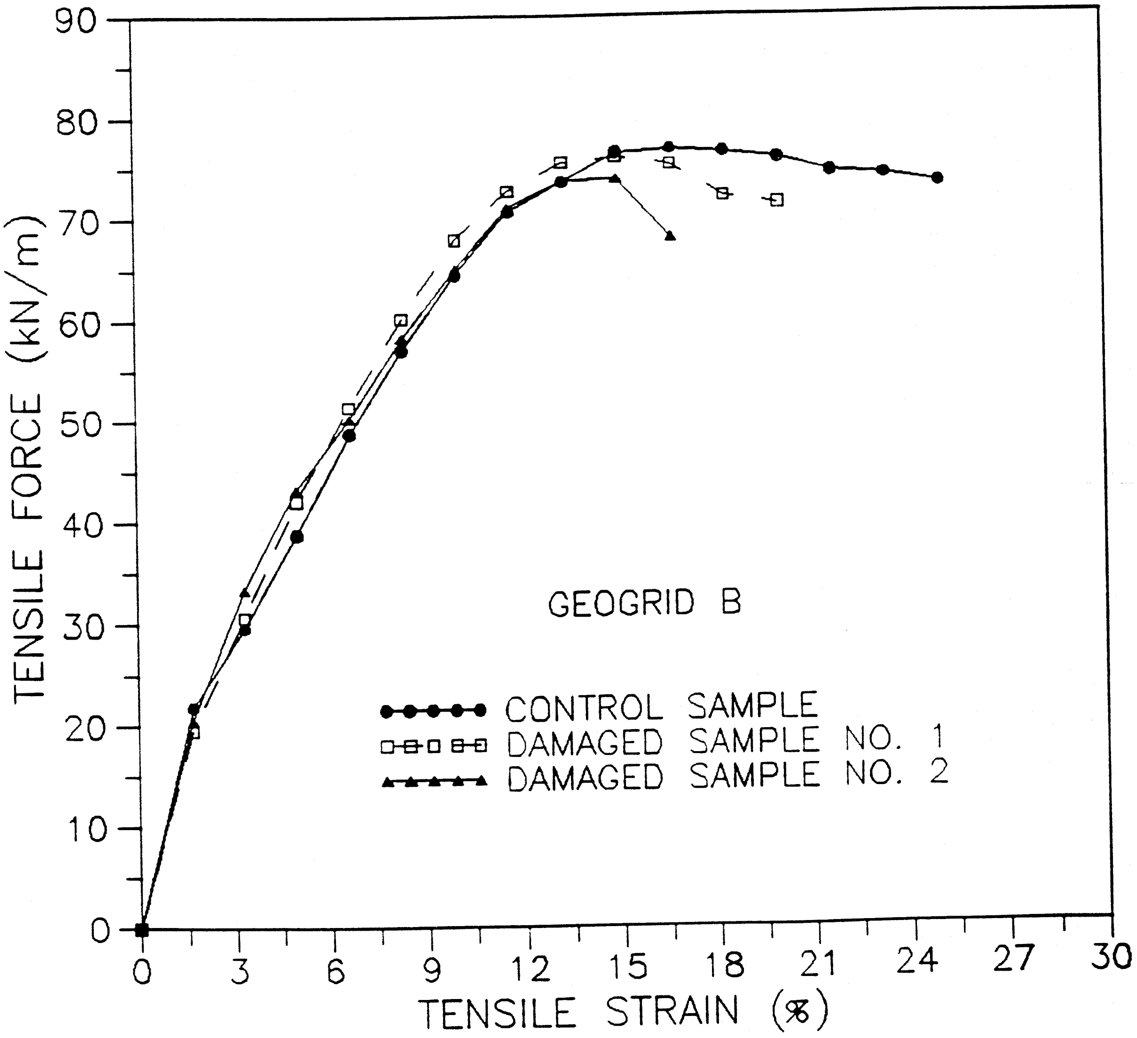

FIGURE 3. WIDE WIDTH TEST RESULTS FOR GEOGRID B

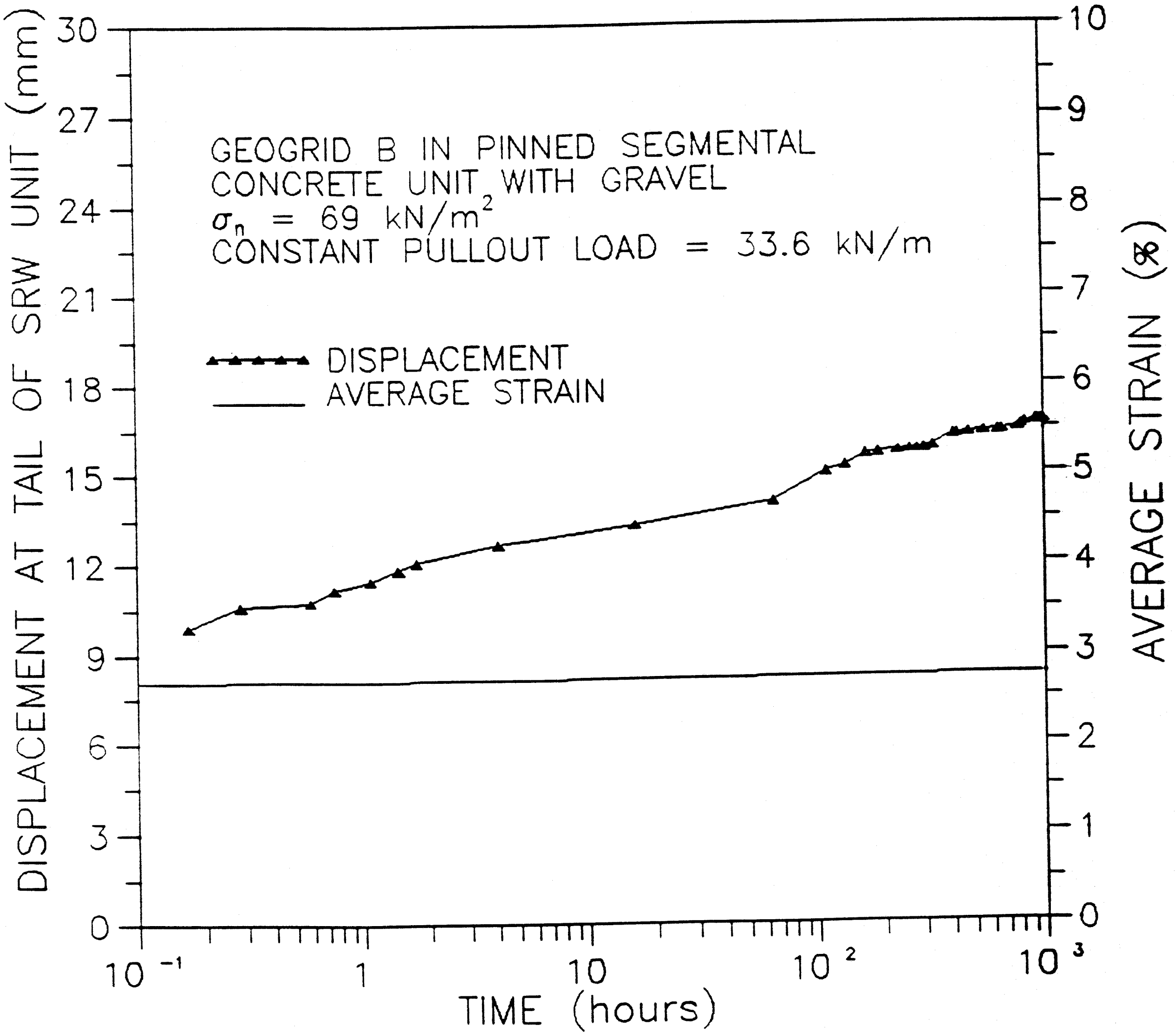

FIGURE 4. LONG-TERM CONNECTION TEST - DISPLACEMENT VS. TIME AND AVERAGE STRAIN RATE VS TIME