Design Loads and Partial Safety Factors for Geogrids in Soil Reinforcement

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ABSTRACT: In this paper, various considerations in the determination of design loads and partial safety factors for geogrids in soil reinforcement are described. Factors considered include the phenomena of stress rupture, creep, hydrolysis, weathering, mechanical damage, chemical and microbiological attack which would lead to degradation of the reinforcement in the long term. These are affected by environmental conditions, of which temperature, humidity, pH and mechanical aggressiveness of the fill used are key factors. The situations particular to Hong Kong are highlighted in these considerations. A brief account of the control system for the use of these products in Hong Kong is then presented.

1 INTRODUCTION

Geogrids manufactured from polymer products are gaining popularity world wide. However, since the recommended design loads of the manufacturers are normally based on the code of practice of the country of manufacture, they may not have been derived consistently and may not even be appropriate for the conditions in Hong Kong. The Geotechnical Engineering Office (GEO) of the Hong Kong Government therefore commissioned a study on the use of polymer geogrids as soil reinforcement under Hong Kong conditions, initially on HDPE and Polyester materials. This resulted in the reports by Small & Greenwood (1993) and Greenwood (1994). This paper gives a general summary of the study on the design load appropriate for Hong Kong.

The key requirements for design conditions in Hong Kong are a service life of 120 years and a service temperature of 35°C. The design method is specified in GEO (1989) and Wong (1993).

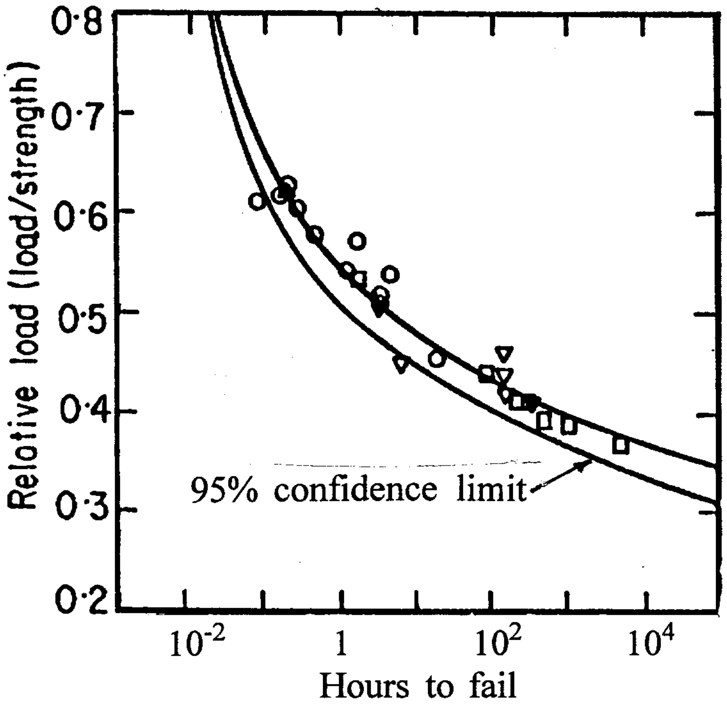
To design reinforced soil structures with sufficient safety, it is necessary to define the partial safety factors f_m, for the material, and f_{env}, for the environment. In BSI (1994), these are given as a general factor f_m which is then subdivided to account for various effects which are described below.

2 STRESS RUPTURE

The long-term design strength is the strength that is available from the material at the end of its design life, frequently as long as 120 years. Since in soil reinforcement a geogrid will be under sustained load for its entire life, the design load should be derived from extrapolated stress-rupture data from consideration of collapse limit state, rather than from creep strain data. Codes of Practice such as GRI (1990) assume that after a certain time, depending on the applied load, the strain rate will stop decreasing and will remain constant up to failure. At lower loads, this constant strain rate is so low that there is an apparent strain limit. While this concept, which derives from the work of Wilding & Ward (1984), may be applicable to drawn polyethylene it is quite inappropriate to polyester, where there is no significant upturn in creep strain on creep rate to warn of impending failure.

Nor is it correct to use, instead of the time to rupture, the extrapolated time to 10% creep strain. Measurements on polyesters, as well as on an early polyethylene grid, now superseded, indicate that rupture can take place at less than 10% strain.

It is normal to predict stress-rupture by extrapolating from measurements of time to rupture at high loads and short times to lower loads and longer times. Such data are plentiful for pipes but as yet rare for geotextiles. One of the best sets of data is for a range of polyethylene grids. When expressed as a proportion of their short-term breaking loads, it is found that the stress-rupture diagrams for the various grids, which are formed by the same process from the same polymer, superimpose (Man & Pang, 1992). Secondly, if the data are plotted as percentage breaking load against the logarithm of time, it is possible to shift the data along the time axis to produce a master diagram (Figure 1). Bush (1990) has already used this method of time-temperature superposition for creep curves on the same products.



Legend: data at 10°C ○
20°C ▽
40°C □

Figure 1 - Times to rupture shifted to 35°C for a HDPE geogrid with 95% confidence limit.

Having derived the master diagram, it is possible to fit a curve. There is no fundamental physical law governing the shape of such a curve apart from the simple kinetic theory attributed to Zhurkov & Tomashevsky (1966) which applies to linear materials with no notching effects and leads to a formula of the type

$$\sigma = A_0 - A_1 \log t \qquad (1)$$

where σ is stress, t is time to failure and A_0, A_1 are constants.

This is not a good fit to the polyethylene data in hand and an empirical formula of the type

$$\sigma = A_0 + A_1 \log (\log t) \qquad (2)$$

was used. This enables the data to be extrapolated.

Until recently, there was little data available on the yarn based geogrids such as those based on polyester fibres. There is, however, a considerable amount of information on polyester fibres themselves. Although their mechanical properties depend heavily upon the method of manufacture, the stress-rupture diagrams have so far proved to be of the form in Equation 1 above (Voskamp & Risseeuw, 1987). Tests on yarns, however, are not in themselves sufficient because they do not take into account any possible weakening during manufacture of the geogrid or construction of the joints. It is essential to have data on the geogrid itself, in addition to the yarn data to give confidence to the extrapolation. Typically at least twelve results are recommended, spanning time durations from 100 to 10 000 hours. On the other hand, however, there is no evidence that data measured on just three, or two, or even single ribs of geogrid are untypical of wider widths. This can be of great assistance in reducing the cost and scale of the testing apparatus required.

Using such methods, it is possible to extrapolate to the design life of 120 years or, commonly, 10^6 hours which equals 114 years. The difference is not significant. This generates an initial value of the design load. This value does not, however, take into account the scatter of the data. Statistical methods exist for fitting confidence limits to data which fit a straight line, namely if the regression line is linear then the lower confidence limit takes the form of a hyperbola, with the result that the predicted lower confidence limit fans out at long durations. This is in line with expectations. If the regression line is not straight, then it is necessary to choose a formula to fit the data and re-plot them as a straight line in order for the statistical method to be applied.

It is the point where the extrapolated 95% (one-sided) lower confidence limit crosses the time ordinate of 10^6 hours that we take as the design load. Typically this might be 32% of breaking load for a polyethylene geogrid and 55-65% of breaking load for a polyester based one.

The effect of temperature on the long-term strength of geogrids has already been accounted for in the time temperature superposition. For polyethylene, the optimum shift (that at which the gradient of the combined curve is a maximum) corresponds closely to one decade of time for 10°C. The corresponding strengths are then read off Figure 1. There is very little temperature dependence of creep strain or stress rupture for polyester fibres below their glass transition temperature at about 70°C. Their short-term strength decreases by about 3% per 10°C and a similar adjustment is made to long-term strength.

3 HYDROLYSIS

The hydrolysis of polyester fibres has received much attention recently. It appears that there are two effects : "internal hydrolysis", which takes place in both alkaline and acid environments, although it may be accelerated at either extreme, and "external" hydrolysis, which occurs in highly alkaline environments and is visible macroscopically in surface pitting and rapid weakening of the fibres. In soil reinforcement it is the first of these that is the more significant. The latter is accounted for by limiting the pH value of the environment.

To accelerate internal hydrolysis and produce degradation of the fibres within a reasonable time, the fibres must be immersed in hot water at 90°C or below (Schmidt et al, 1994). Fibres extracted exhibit a loss in strength and a reduction in molecular weight which can be measured as a change in intrinsic viscosity. The data can be extrapolated by using Arrhenius' formula which can be written as

$$\ln t_1 - \ln t_2 = (E_A/R)(1/T_1 - 1/T_2) \qquad (3)$$

where t is the time to reach a certain point in the reaction, E_A is the activation energy, R is the gas constant (8.31 J/K/mole) and T is the absolute temperature. Extrapolation can be performed by determining the time-strength relationship at different temperatures, plotting the logarithm of time against reciprocal temperature and extrapolating to the service temperature, or more fundamentally by using the intrinsic viscosity measurements and molecular rate kinetics to deduce the change in molecular weight and thence the reduction in strength. The activation energy of the process lies in the range 105-115 kJ/mole. It must be noted that extrapolation is across the transition temperature, for which a safety factor is allowed.

Using this method, it is possible to derive a reduction in strength due to hydrolysis. While this is estimated to be only a few percent at 20°C, the acceleration with temperature is such that at 35°C the strength would have fallen to 60-70% of its initial value after 10^6 hours, and at a continuous temperature of 40°C the use of polyester fibre geogrids becomes questionable. Since most sheath materials are permeable to water vapour, the effect of the sheath is discounted, and the geogrid is assumed to be in a saturated vapour or liquid. In not fully saturated environments, the rate of attack is believed to vary with the relative humidity.

4 PARTIAL SAFETY FACTORS FOR OTHER EFFECTS

Partial safety factors must then be applied to cover the following:

4.1 Lack of confidence in the data

A factor for lack of confidence in the data would be applied, for example, if the number of data points was less than twelve, or if the data had been generated on a different product without sufficient demonstration that they could be transferred. A typical factor for the latter case would be 1.25.

4.2 Lack of confidence in the method of extrapolation of stress rupture data

The method of extrapolation is crucial to the calculation of design strength and it is easy for the logarithmic time scale to instil over-confidence. BSI (1994) recommends a factor of 1.0 to be used for extrapolations of up to ten times (one decade), increasing with the logarithm of time to a factor of 2.0 for extrapolations of 100 times (two decades). An additional condition is that tests should be set up and allowed to run to 10% of the design life - 12 years for a design life of 120 years - and possibly beyond, in order to validate the assumptions. It should be noted, however, that this factor recommended by BSI (1994) includes items that are handled separately in this analysis, and we have recommended factors as low as 1.3 to cover uncertainty in extrapolation for the data in Figure 1, where time-temperature superposition is used.

4.3 Possibility that the strength may be less than the nominal value

Most manufacturers quote characteristic or guaranteed strengths for their products. Frequently, however, independent measurements are available, often as part of other measurements such as damage assessments, and if any of these are noticed to fall below the quoted strength of the material an additional safety factor should be applied.

4.4 Temperature in excess of the design temperatures

In polyolefins which are sensitive to temperature, one excessively hot day can, according to current thinking, have the same effect as many days at the design temperature and is not compensated for by the equivalent time at lower temperatures. Sub-soil temperatures 13 mm below a concrete slab in Hong Kong were shown to reach 40°C (Howells & Pang, 1989). However, a temperature of 40°C for, say, 180 hours a year, increases the "lifetime" by 8% over that at the design temperature of 35°C, and in Hong Kong this design temperature is regarded as adequate without any additional safety factor.

4.5 Changes in the mode of rupture

In unoriented polyethylene pipes, there is transition from ductile to brittle fracture at intermediate stresses, leading to lower lifetimes than extrapolation would have been predicted. Seen the other way round, the normal brittle failure of unoriented polyethylene is obscured at loads high enough to produce premature ductile failure. The nature of the failure can be seen clearly from the fracture surface. We have examined the long-term failures of one type of polyethylene geogrid and have found only one mode of failure, a semi-brittle mode that occurs at about 10-20% strain. Only if a stress concentration is deliberately induced into the unoriented section of the nodes would it be possible to produce the brittle failure characteristic of pipes. Nevertheless, extrapolation of stress-rupture is critically dependent upon the mode of failure remaining the same. In view of the unlikely but possible transition, a subjective factor of 1.1 is applied to all polyethylene grids.

4.6 Junction strength and soil interlock

There are basically two considerations for the joint strength. The first is the connection between two geogrids required by construction. The concern here is whether it forms a weak link in the axial tensile strength of the reinforcement as a whole. When it occurs in the maximum tension zone, a partial factor or joint efficiency factor should be applied.

The second is the junction between transverse and longitudinal grids. The concern here is whether it plays any part in the load transfer from soil to the reinforcement. If the soil locks to the transverse ribs of a geogrid, then most of the load is transferred across a few junctions into the longitudinal members. Long-term failure of these junctions could lead to stripping of the geogrid and immediate pull-out. If on the other hand the load is transferred from the soil to the longitudinal members by friction, the transverse ribs act as no more than spacers. This would depend to some extent on the anchor length provided, and the nature of the soil. This should be considered in the design of anchor length.

4.7 Short-term and long-term effects of mechanical damage

Mechanical damage is taken into account by a partial safety factor equal to the ratio of the pristine strength to the strength of the material after compaction in the fill. Such factors range from 1.0 for sand and clay to over 1.5 for aggressive fills. In using such factors for long-term strength, one is assuming that the gradients of the stress-rupture curves with and without damage are parallel. There are too few results available at present to establish whether they in fact diverge, run parallel, or converge, and until this is known and additional factor of 1.1 is recommended.

4.8 Chemical and microbiological attack

The effects of chemical and microbiological environments on geogrids are still under investigation. It is the intention behind the index tests being developed by CEN TC 189 to guarantee a minimum level of durability in, for example, normal soils between pH4 and pH9 below 20°C. Polyethylene geogrids have so far been shown to be inert to chemicals both with and without the presence of superimposed load, and with hydrolysis having already been taken into account for polyesters it is our practice to recommend special testing if polyesters are to be used at pH9 or above. There is no evidence for environmental stress-cracking (synergy between load and chemical environment) in the heavily drawn material, although this is well known in oreinted geomembrane material.

4.9 Uncertainty in the method of extrapolation for hydrolysis

The extrapolation of the hydrolysis data is, as noted, very tentative at present, and safety factors are applied based on the rate of hydrolysis being approximately twice that calculated. Converted back into strength calculations, this results in safety factors ranging from a minimum of 1.1 at 20°C to 1.5 or greater at 35°C.

4.10 Weathering

The well-known effect of the ultraviolet section of solar radiation on polymers has led to the development of efficient additives to delay the effect. Most geotextiles are destined to be covered by soil or vegetation in service. It is the intention of the CEN test to provide assurance of resistance to 6 months of exposure under normal Northern European climate, or, since the global radiation in Hong Kong is twice as great, three months in Hong Kong. It is expected that the site rules will ensure that exposure is limited to this amount and therefore no additional safety factor is applied.

5 CREEP

Creep is considered in the estimate of long term strain for the serviceability limit state. More data are available for creep strain than for stress rupture. As indicated above, certain geogrids are more sensitive to temperature. It is important to have data obtained near the maximum anticipated service temperature, which is 35°C for Hong Kong. An upper limit (maximum strain) must be defined to account for variability in data, which we have noticed particularly at low strains in polyester geogrids. Extrapolation should follow BSI (1994). Mechanical damage, chemical and microbiological attack and weathering do not affect creep strain except at very high levels of degradation when failure is imminent. It is therefore important to recognize the difference between partial factors of safety applied to stress-rupture for collapse limit state and those applied to creep strain for serviceability state.

6 DATA SUBMISSION FOR HONG KONG

The Geotechnical Engineering Office (GEO) of the Hong Kong Government introduced in 1989 an Endorsement Certificate System for the prior approval of proprietary products intended for use in permanent reinforced fill structures in Hong Kong, and three Endorsement Certificates have been issued so far. The manfacturers are required to provide data to justify the design loads and partial factors on their products appropriate to the Hong Kong environment. They are also required to have a quality assurance scheme equivalent to the standard of ISO 9002 for their products. The endorsement certificates are reviewed annually so that the latest data and field performance of prototype structures can be taken into account in the consideration on the design load. The details are described in Man & Pang (1992) and Man & Pang (1994).

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ACKNOWLEDGEMENTS

This paper is published with the permission of the Director of Civil Engineering of the Hong Kong Government and the Directors of ERA Technology Ltd of UK. Various manufacturers and colleagues have provided valuable data and comments during the course of the study. Their assistance are gratefully acknowledged.