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Strain Compatibility in the Stability of Embankments Reinforced at the Base with Geosynthetics on Soft Soils

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Abstract. This paper presents a summary and comments regarding the use of a method for the stability analysis of embankments reinforced at the base with geosynthetics on soft soils, considering strain compatibility as proposed by Hinchberger and Rowe (2003). The method presents an important understating about the behavior of reinforced embankments on soft soils and the needed strain compatibility between the reinforcement and the foundation soil. Such compatibility is to ensure that the tensile resistance of the reinforcement is engaged before the soil reaches the plastic zone at large deformations, which would characterize failure of the embankment, even before the full mobilization of the reinforcement resistance is achieved. The method is based on the observation of instrumented sites and on a large parametric study applying numerical models. A correct stability analysis to establish the required reinforcement resistance, and the choice of a compatible reinforcement tensile modulus for the joint mobilization of the foundation soil, embankment fill and reinforcement strengths are essential for the construction of safe and not excessively deformed embankments.

Keywords. Soft soil, geosynthetics, geogrid, strain, deformation, tensile modulus, stiffness.

1. Introduction

This paper presents a summary and important comments regarding the use of a stability analysis for reinforced embankments on soft soils method, which considers strain compatibility as proposed by Hinchberger and Rowe [1]. The method is based on observation of instrumented sites and a large parametric study with numerical models, it considers important points regarding the use of reinforcement with a tensile modulus compatible with the soft soil foundation deformation, before the soil reaches its plastic zone (herein also referred to as plasticizing). The paper does not provide a deep analysis of the theory, nor of the study completed by the developers of the method. Instead, it seeks to simplify the results and the proposals for design of embankments reinforced with geosynthetics. Its goal is to optimize safety by offering a method for correctly choosing the reinforcement specifications.

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2. Importance of the Topic

The use of basal reinforcement for embankments on soft soil is common engineering practice in many countries. The technique is very simple resulting in safe structures, with reduced deformation, no crack development nor rupture. However, reinforcement design is not trivial, some methods can result in over estimation of the required tensile strength and underestimation of the tensile modulus.

Instrumented embankment structures and unsuccessful cases have shown that reinforcement with high tensile strength and low tensile modulus can cause embankment rupture due plasticizing of the foundation and large deformation without total mobilization of the tensile resistance of the reinforcement. On the other hand, reinforcement with high tensile modulus and insufficient tensile resistance can rupture before the foundation soil resistance is developed.

A stability analysis for the correct determination of the required reinforcement strength and tensile modulus for the combined mobilization of foundation soil, embankment and reinforcement is essential for optimized, safe structures with low deformation.

3. Method Proposed by Hinchberger and Rowe

For around two decades, researcher Robert Kerry Rowe observed and instrumented embankments on soft soils, very soft soils and peat, built with different techniques including reinforced earth. He observed that construction of embankments in a short period presents three typical behavior phases: at the beginning of loading, at the foundation soil plastic zone and at rupture of the foundation soil.

Figure 1 shows a typical cross section for a base reinforced embankment on undrained soft soil, with undrained strength at the surface (S_{u0}) and S_u strength gain ratio ρS_u. Figure 2 shows the typical observed behavior as the embankment is built on a short period under undrained conditions.

Figure 2 defined the net height, which is the total embankment height minus the settlement as the construction progresses, it can be understood as the elevation gain during the embankment construction.

The net height versus the total embankment height, or fill height is shown on the left side of Figure 2. An almost linear section can be noticed where the embankment construction results almost directly into height gain, in other words, there is practically no settlement at the base. From a certain height (in this case 1,8 m), the embankment thickness gain results into a smaller net height gain, in other words, the base of the embankment shows significant settlement, therefore indicating the beginning of the foundation soil plastic zone. The soft soil, which until then showed an approximately elastic response, starts a plasticizing process with increased shear and settlement deformations under undrained conditions. This behavior speeds up to an embankment fill thickness of approximately 2,4 m, with an equivalent net height of 2 m. At this phase the whole embankment foundation plasticizes and large deformations occur, including sinking of the embankment which characterizes foundation rupture.

The maximum reinforcement strain versus embankment fill thickness is shown on the right side of Figure 2. It can be noticed that in the initial phase, up to a height of 1,8m the strain is small and less than 1%. When the foundation soil plasticizing process starts the strain increases up to 5,1 % when the foundation fails. After the foundation ruptures the soft soil loses strength and the stresses in the reinforcement increase even more, the deformation are very large and the structure collapses, even if the reinforcement has not ruptured. Based on this figure, it can be noticed that a good design for basal embankment reinforcement must predict the required strength so the structure will not rupture, due to foundation plasticizing or by reinforcement rupture. On this case, the correct design should predict the required strength mobilization to ensure the stability of the embankment at the height of 2 m with a reinforcement strain of approximately 1 to 2%. The use of a reinforcement too strong with low tensile modulus which does not mobilize the resistance at strains from 1 to 2%, means that the reinforcement will not be activated in the beginning of the foundation plasticizing process and it will provide little contribution towards stability. On the other hand, it must be assured that a reinforcement with very high modulus can also provide the required resistance for the stability of the structure for a height of 2 m, which is the safe height for this situation, with a minimum factor of safety of 1,2 for the rupture embankment thickness of 2,4 m.

In summary, the maximum rupture height for a reinforced embankment must be designed through calculations to establish the required reinforcement resistance while also allowing the reinforcement to mobilize such resistance at small deformations, compatible with the beginning of the foundation soil plasticizing process. Therefore, the embankment will be stable, with an adequate factor of safety and small deformation during construction since the reinforcement will limit horizontal deformation at the base.

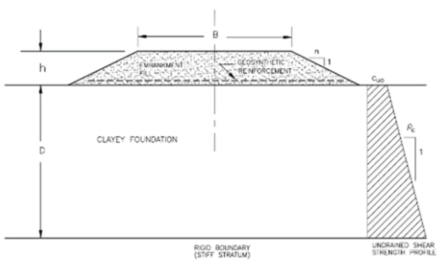

Figure 1. Example of embankment cross section.

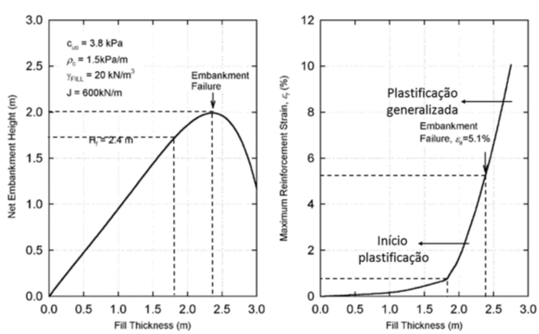

Figure 2. Net embankment height and reinforcement strain.

Figure 3 shows rupture plasticizing regions for embankments on very soft soils with S_{u0} of 5 kPa and on soft soils with S_{u0} of 16 kPa and ρS_u of 1,5 kPa. It can be seen that the embankment height is larger when the foundation soil strength is higher; also the plasticizing zone is different. The foundation plasticizing zone and its transition from the beginning of the process to a generalized plasticizing are larger in stronger soils. Consequently, reinforcement strain can also be larger before the foundation rupture occurs.

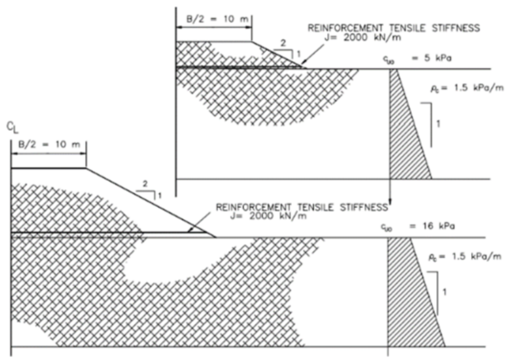

Figure 3. Plasticizing zones.

From a parametric study with numerical models and by adopting an elastic plastic behavior for the embankment's foundation soil, Hinchberger and Rowe [1] determined the critical (collapse) unreinforced embankment height (H_c) for many situations, where the foundation soil's generalized plasticizing occurred with large deformations and net embankment height loss. Then, with the same conditions and same undrained foundation soil strength, numerical analyses considering the addition of basal reinforcement were used to determine reinforcement strain for the corresponding critical heights. Such strain, relating reinforcement to the critical height (H_c) was named "maximum compatible strain" (ε_a) and it is shown on Figure 4 for many strength S_u increase of undrained shear strength with depth (ρS_u).

The plot is not explicit regarding the undrained strength at the top of the soft soil layer (S_{u0}), which is normally the governing parameter for the critical height of embankments. The authors opted to the direct use of the critical height (H_c), which comprises other factors as the undrained strength at the top itself, the thickness of the soft soil layer and embankment slopes. Therefore, the critical height for an unreinforced embankment with a specific geometry must be previously known. Such height can be obtained through specific limit equilibrium analysis, using for example computer programs or available simplified abacus.

The allowable (compatible) strain (ε_a) is the strain at the exact moment when the foundation soil generalized plasticizing and net embankment height loss occur, which indicates failure by excessive deformation but not necessarily reinforcement rupture. In reality, what is desired in a project is the existence of a factor of safety that the reinforcement has enough strength and its tensile modulus is high enough so the reinforced embankment height is always less than the critical height and the reinforcement strain is quite smaller than the maximum compatible strain. Therefore, the reinforcement must always mobilize its strength before the compatible strain, as shown on Figure 2 where the foundation soil plasticizing process starts with a typical critical height factor of safety of 1,2. Some designers who understood that the reinforcement must always be designed to resist strain equal to or larger than the maximum compatible strain and that high modulus reinforcement can rupture before the embankment reaches its critical height have incorrectly interpreted this observation. In fact, the method states the contrary: the reinforcement must have much higher tensile modulus (stiffness) in order to mobilize the required strength at a strain smaller than the maximum compatible limit. The reinforcement strength required for embankment stability is not part of the proposed method and must be obtained from coherent limit equilibrium analyses so the reinforced embankment is always below the limit height, with small deformation and strain always less than the proposed maximum compatible strain. The higher the reinforcement tensile modulus the better, as long as its strength is higher than the one calculated using limit equilibrium analysis.

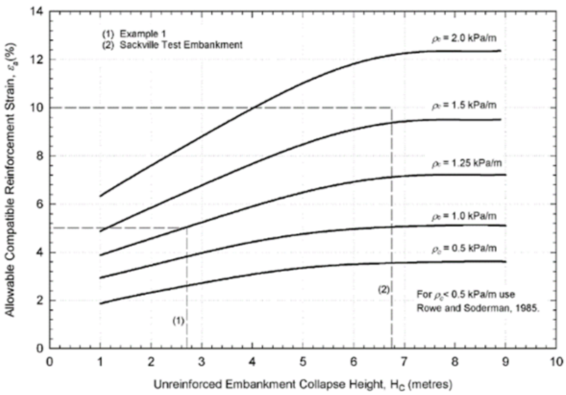

Figure 4. Maximum strain compatibility versus unreinforced critical height.

According to Futai [2], other factors as for example the existence of equilibrium berms, surface sand layer or use of vertical drains can affect the determination of the maximum compatibility strain.

4. Design Sequence According to Hinchberger and Rowe Method

The design sequence for a reinforced embankment according to the proposed method follows a quite simple, although different from the methodologies normally used, especially regarding the addition of a partial reduction factor for the undrained strength of the clay instead of the traditional global factor of safety. The undrained strength and the strength with depth gain ration are typically reduced by a factor or 1,3 and the sequential limit state calculations are done using a factor of 1,0. Therefore, the critical height is already reduced and the reinforcement required design strength calculated through limit equilibrium is already increased. The design strength must be converted to characteristic reinforcement tensile strength only through the application of the adopted damage, durability and creep reduction factors. Even if the use of the creep reduction factor may not be fully accepted, since the construction occurs under undrained conditions which is a load of medium duration, the use of a creep reduction factor for a least one month is always recommended. The final loads for the project can be disregarded or only partially considered since in the short term, the final pavement is still not present and the final highway loads for example, will not be occurring yet. However, temporary surcharges for speeding up settlement and additional height for compensation of future settlements must be considered as part of the project height.

The design takes place in the following stages:

a) Characterization of the fill geometry and parameters (height, platform width, slopes, surcharges, unit weights, friction angles and cohesion) and characterization of the foundation undrained strength at the surface and ratio of strength gain with depth. The undrained strength is the main design parameter and it must be determined through lab and in situ tests.
b) Reduction of the undrained strength and ratio of strength gain with depth. In general, the initial values are divided by 1,3 and the reduced values are used in the design.
c) Calculation of the unreinforced embankment critical height with the reduced undrained shear strength. The critical height can be obtained through limit equilibrium methods or through available simplified graphs.
d) Calculation of the maximum height considering reinforcement with infinite strength and modulus. This consists of estimating the maximum height for a completely rigid embankment. Available graphs for plastic solutions rigid loads are used for such (for example, the solution proposed by Rowe and Soderman [3] shown in Figure 5.

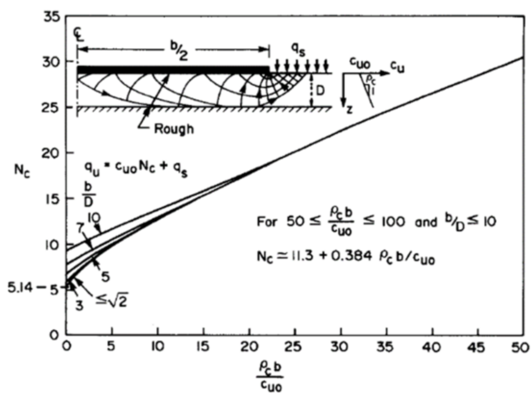

Figure 5. Graph for calculating the maximum plasticization height considering the perfectly rigid embankment.

e) If the project embankment height is smaller than the unreinforced critical height, then the embankment is stable and does not require basal reinforcement. If the project embankment height is larger than the maximum height obtained in d, then the reinforced solution is not sufficient by itself. In such case, a study of other alternatives, like the use of balance berms, staged construction or soil improvement methods should be considered. If the project height is larger than the unreinforced critical height and lower than the maximum possible height, then the basal reinforcement solution can be used.
f) Limit equilibrium analyses considering the reinforcement strength, should target a factor of safety equal to 1,0 for the project height. Analyses software like Slide, GeoSlope and others with an automatic search for critical surfaces considering the reinforcement strength are recommended. The reinforcement strength must be changed until a factor of safety equal to 1,0 is obtained.
g) The reinforcement strength obtained for a factor of safety of 1,0 is the reinforcement design strength for the project. For the selection of the reinforcement, such strength must be multiplied by the manufacturer certified

reduction factors (for installation damage, environmental degradation, and typically for one-month creep since the construction is quick).

h) The maximum compatibility strain can be obtained from the graph shown in Figure 4 using the unreinforced critical height and the reduced undrained shear strength gain with depth ratio. The strain for the required working stress resistance will be equal or smaller than the value obtained from the graph. If the reinforcement has a small modulus and it cannot mobilize the required stress at a strain smaller than the maximum compatibility Strain the foundation soil will suffer plasticization and the embankment will fail with large deformations since the reinforcement cannot mobilize the required strength at a compatible strain.
i) To establish the minimum required reinforcement modulus the calculated required resistance is divided by maximum compatibility strain. The reinforcement must meet the working stress requirement (reduction factors must be included) at strains equal or smaller than the maximum compatibility strain. A high modulus reinforcement that would fail at a strain similar to the maximum compatibility Strain can be used since it meets the required strength and its resistance will be mobilized at a height smaller than the critical limit with strain smaller than the maximum compatibility strain and the embankment will be stable.

It is important to emphasize that the calculations are done with a factor of safety of 1,0 but the undrained shear strength is typically reduced by a factor of 1,3. In practical terms that means that the project height is smaller than the reinforced embankment limit height with a margin of approximately 1,3. In other words, according to **Figure 2**, the reinforcement strain will still be very small when the embankment reaches the project height. It is important that the reinforcement has a high modulus, preferably mobilizing the required resistance at a strain between 2 and 3%, independently of the estimated maximum compatibility since its function is to restrict horizontal movements at the base of the reinforcement to warrant small deformations by confining the embankment and to prevent plasticization of the soft soil foundation.

5. Worked Example

a) Embankment base of 20 m, project height of 3,5 m, unit weight 19 kN/m^3, cohesion of 5 kPa and internal friction angle of 25°. Side slopes 4H:1V, on a 10 m thick very soft marine clay layer with unit weight of 14 kN/m^3. S_{u0} at the surface of 6 kPa and ρS_u of 1,5 kPa per meter of depth.
b) Factored undrained shear strength: $S_{u0} = 6/1{,}3 = 4{,}62$ kPa, $\rho S_u = 1{,}5/1{,}3 = 1{,}15$ kPa /m
c) Unreinforced embankment collapse height $H_c = 2{,}6$ m (Figure 6) obtained using Bishop's method.
d) Collapse height for the perfectly rigid embankment: rigid embankment base of 3,5 m. B = 3,5 x 4 x 2 + 20 = 48 m, ρS_u x b / S_{u0} = 1,15 x 48 / 4,62 = 11,95, N_c = ~14,5 (Figure 5), $H_u = N_c \times S_{u0} / \gamma_{embankment}$ = 14,5 x 4,62 / 19 = 3,53 m
e) The embankment requires reinforcement since the project height (3,5 m) is larger than the unreinforced critical height (2,6 m). The project height is smaller than the collapse height for the perfectly rigid embankment (3,53 m), therefore the basal reinforced embankment solution can be used.

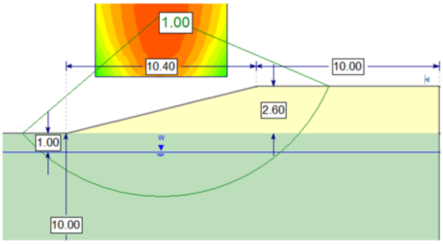

Figure 6. Unreinforced embankment collapse height, H_c.

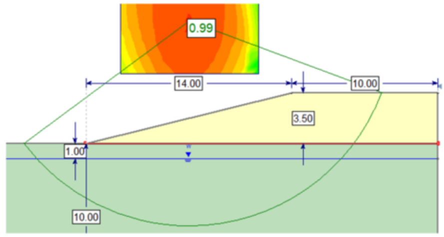

Figure 7. Required tensile reinforcement strength H=3,5 m with FS=1.

f) Calculation of the required tensile reinforcement strength for a height of 3,5 m (Figure 7) – T= 65 kN/m
g) Assumed reduction factors: for installation damage (1,1), environmental degradation (1,0), one month creep (1,4). Calculation of the required characteristic reinforcement strength: 65 x 1,1 x 1,4 = 100 kN/m.
h) Maximum compatibility strain obtained from Figure 2 with H_c=2,6 m and ρS_u=1,15 $\Rightarrow \varepsilon_a$ = 4,2%.
i) For the most critical condition where reinforcement must resist 65 kN/m (calculated) with a limit maximum elongation of 4,2%, the minimum reinforcement modulus shall be 65 / 0,042 = 1.548 kN/m. Therefore, the specifications shall be: reinforcement characteristic strength ≥ 100 kN/m (for a global reduction of ≤ 1,54) and reinforcement tensile modulus ≥ 1.548 kN/m.

Comparison of materials with different deformations at the required strength:

Table 1. Reinforcement options discussed for the example.

Item	**Tensile strength**	**Tensile modulus**
Geogrid A ε ≤ 5%	100 kN/m (meets requirement)	2.000 kN/m (meets requirement)
Geogrid B ε ≤ 10%	100 kN/m (meets requirement)	1.000 kN/m (does not meet requirement)
Geogrid C ε ≤ 10%	155 kN/m (meets requirement)	1.550 kN/m (meets requirement)

ε: Reinforcement strain at the characteristic strength

If a geogrid with 10% elongation at ultimate strength would be adopted, a material with a characteristic resistance of 10% x 1.548 = 155 kN/m should be chosen according to the strain compatibility criteria. For this example, a geogrid with 10% elongation, tensile strength of 100 kN/m and modulus of 1.000 kN/m would meet the required strength according to the limit equilibrium (65 kN/m) analysis, but it would suffer a strain of 6,5% at the working stress level and therefore it would not meet the compatibility strain criteria (4,2%). In other words, the embankment would fail due to the fact that the foundation soil would reach the plastic zone under large deformations before the reinforcement mobilizes the required resistance. If a geogrid with 5% elongation at ultimate strength was chosen a minimum strength of 5% x 1.548 = 78 kN/m would be required, but according to item g the reinforcement needs a minimum strength of 100 kN/m so there is no rupture.

The project has a factor of safety of approximately 1,3, so it is desirable that the reinforcement mobilizes its strength of 65 kN/m at strain even smaller than the compatibility strain. Some international regulations limit such strain at 5%, other references suggest a working condition at 3% for embankments at the limit of reaching the plastic zone. By following this criteria, the reinforcement modulus should be 65 / 0,03 = 2.166 kN/m, which could be obtained with a geogrid with strength of 216 kN/m and an elongation of 10%, or with a geogrid with 108 kN/m at an elongation of 108 kN/m, resulting with the same results in terms of embankment deformation and foundation plasticization. In both cases, the reinforcement meet the required 100 kN/m of nominal resistance and have a minimum modulus of 2.166 kN/m, mobilizing a strength of 65 kN/m at 3% elongation.

6. Conclusions

The calculation method presented by Hinchberger and Rowe (2003) shows an important understanding of how reinforced embankments on soft soils behave. It also show the need for strain compatibility between the foundation soil and the reinforcement so the reinforcement is effective and capable of mobilizing tension resistance before the foundation soil failure process starts by suffering large deformations even before the reinforcement is completely mobilized.

Traditional limit equilibrium analyses are used to determine the unreinforced embankment critical height, the maximum possible height considering a perfectly rigid embankment (maximum possible reinforcement) and mainly, to obtain the reinforcement design strength for embankment stability at a certain height.

The method incorporates a verification after the reinforcement design strength has been completed in order to establish a reinforcement tensile modulus such so its strain is smaller than the strain that would cause foundation soil plasticization before the complete mobilization of the reinforcement resistance. The maximum compatibility strain varies between 2 and 12%, and depends on the unreinforced embankment critical height (embankment's geometry, foundation soil undrained shear strength at the surface) and on the undrained shear strength gain with depth. Generally, the maximum compatibility strain is higher for soil with higher undrained shear strength. The critical situation occurs in very soft marine clays.

In engineering practice, projects are designed with a factor of safety so the soil does not reach a generalized yielding state, and for such the deformation of the reinforcement must be even smaller, in the range between 3 and 5% at the most according to some regulations and available literature.

High modulus reinforcement are always more efficient for embankment safety and to keep deformations small regardless of the polymer used to make the reinforcement. The same result can be obtained with geogrids made with different polymers (polyester, PVA or aramid for example), as long as they have the same modulus, which implies higher characteristic tensile strength for polymers with smaller modulus.

The fact that a polymer made with a specific reinforcement may have an ultimate elongation smaller than the maximum compatibility strain does not mean that it will rupture due to an excessive strength requirement. On the contrary, if the reinforcement has a higher modulus, it will mobilize the required resistance (project's design strength) to stabilize the embankment at smaller strains. What defines if the reinforcement will rupture is not its modulus but the calculation of the project design strength completed through limit equilibrium analyses. Once the strength is calculated and the reduction factors for installation damage, environment degradation and creep are applied the higher the modulus to achieve that resistance at smaller deformations the better the performance and stability of the embankment.

References

[1] Hinchberger, S.D. and Rowe, R.K. (2003) Geosynthetic Reinforced Embankments on Soft Clay Foundations: Predicting Reinforcement Strains at Failure, Geotextiles and Geomembranes, Elsevier, Vol. 21, p. 151-175.

[2] Futai, M.M. (2010) Considerações sobre a Influência do Adensamento Secundário e do Uso de Reforços em Aterros sobre Solos Moles, Tese de Livre Docência, Departamento de Estruturas e Geotecnia da Escola Politécnica, Universidade de São Paulo, 197 p.

[3] Rowe, R.K. and Soderman, K.L. 1987 Stabilization of very Soft Soils Using High Strength Geosynthetics: the Role of Finite Element Analyses, Geotextiles and Geomembranes, Elsevier, Vol. 6, p. 53-80.