Reinforced soil embankments design and construction

P. Jackson
Comet, UK

S. Corbet
Maunsell Ltd, UK

A. Kjeld
Byggros A/S, Denmark

Keywords: Railways, Reinforcement, Geogrids, Case Study, Code of Practice

ABSTRACT: This paper describes the design, construction and monitoring of the steep faced geogrid reinforced embankments that have been constructed to support parts of the Copenhagen Metro. The embankments have been constructed using a coated polyester geogrid, which reinforces locally won as-dug granular fill. The faces of the embankments are formed using a propriety galvanised steel mesh facing. As a temporary expedient the geogrid in the facing is protected from degradation by a UV-stabilized non-woven polypropylene geotextile.The construction of the embankments was carried out during the period June 1998 to November 2000. The track laying and installation of the signaling and other services was complete during early 2000. Trial running of the metro trains has now commenced. Several sections of the embankment were instrumented with movement monitoring gauges; data from the construction records and the instrumentation are presented with details of the design and procurement procedures.

1 INTRODUCTION

The Copenhagen Metro is a challenging project, which is being constructed by the COMET group, a joint venture of Carrillion, SAE, Bachy Soletanche, Ilbau, Astaldi and NCC for the client Ørestadsselskabet. The project is to construct a new Metro system linking the historic central part of Copenhagen with the suburbs to the North West and the Island of Amager to the South. The leg of the Metro running down the Western part of Amager forms the major transportation link for the Ørestad new town development. This leg of the Metro, is constructed above ground and is approximately 5km in length. Part of this is constructed on reinforced concrete viaducts with the remainder (2.2km) on steep faced geogrid reinforced soil embankments. The face of the reinforced soil embankments was required to be very steep, at an angle of 78.9° to the horizontal (or 5 vertical to 1 horizontal).

The route of the metro is shown in Figure 1 with the reinforced embankment sections marked.

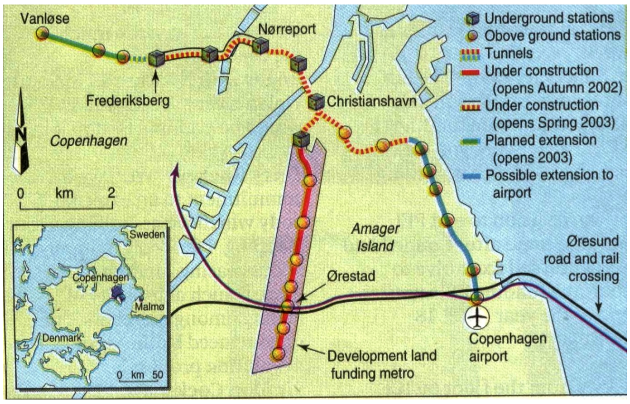

Figure 1: Plan of the Copenhagen Metro

2 TENDER DESGNS

During the tender period Maunsell Ltd. prepared an outline design for the reinforced soil embankments. The design was prepared using conservative parameters for the soil to be reinforced. The concept which was developed for pricing, was for an embankment constructed using soil arising from the works, consisting a mixture of stiff clay and glacial sands / gravels, reinforced using a coated polyester geogrid.

The tender design included two full width base layers of geogrid, to satisfy the overall stability mode of failure, which allowed for the presence of soft layers within the embankment which were thought to be a risk.

3 POST TENDER DESIGNS

Once the contract had been awarded to the Joint Venture, detailed ground investigations were carried out which showed that the soft layers were less extensive than assumed in the tender design and where present were removed and replaced with better quality fill. The full width base layers of geogrid were shown by calculation, overall stability calculations to ENV1997-1, to be un-necessary and were deleted from the final designs.

The project specification required that all geotechnical works on the Metro project be designed using the procedures set out in the pre-standard, Eurocode for Geotechnical Design, EC7, ENV 1997-1. The use of EC7, ENV 1997-1, for the design of geotechnical works, which include geosynthetic reinforcements, is widely recognized as not being practical and unsafe designs can result. The UK forward to ENV 1997-1 acknowledges this and includes a reference to BS 8006 in the National forward, the Danish forward does not have a corresponding reference. It was agreed with the Employer that the designs would be prepared using the provisions in BS 8006.

COMET invited tenders from four suppliers of geogrid soil reinforcement products on the basis that the suppliers would design, supply and install the soil reinforcement using fill materials supplied by COMET, either from elsewhere in the works or from off site sources. Maunsell Ltd. provided a specification for these works, which included soil parameters, and a requirement that the designs needed to be prepared using the principles set out in ENV 1997-1 or BS8006. Tenders were received from the major suppliers of these reinforcement systems and after careful comparison of the tenders, Byggros was appointed to provide a detailed design and supply their Vector Wall facing system with Fortrac geogrid reinforcement. A design life of 100 years leads to a design consisting of two independent structures. Geogrid reinforcement was included as the structural part, to ensure the overall stability of the embankment. As a non structural part, a galvanized steel mesh facing was fully integrated into the system to minimize mechanical damaged, to reduce the effect of fire on the face of the slope and also to act as formwork and a security fence during the construction of the embankment. The non-structural parts were designed in such a way that a later repair or exchange of the galvanised facing mesh and integrated parapet structure should be possible, without interfering the overall stability of the embankment.

The detailed design was prepared using a spreadsheet design program developed to include the principles and partial factors in Section 7 of BS8006. The design spreadsheet is based upon Jewel's Improved Design Charts, Jewell 1994, the material partial factors used are those set out in BBA certificate 97/RO96. In addition to the normal partial factors set out in BS 8006 and the geogrid BBA certificate an additional partial factor was introduced to the design to recognise that the face angle of the embankments was steeper than 70°, the maximum slope angle for which the BBA certificate is valid, and that the structure is in the 'high risk' category for both BS 8006 and ENV1997-1. A typical graphical output from the spreadsheet is shown in Figure 2.

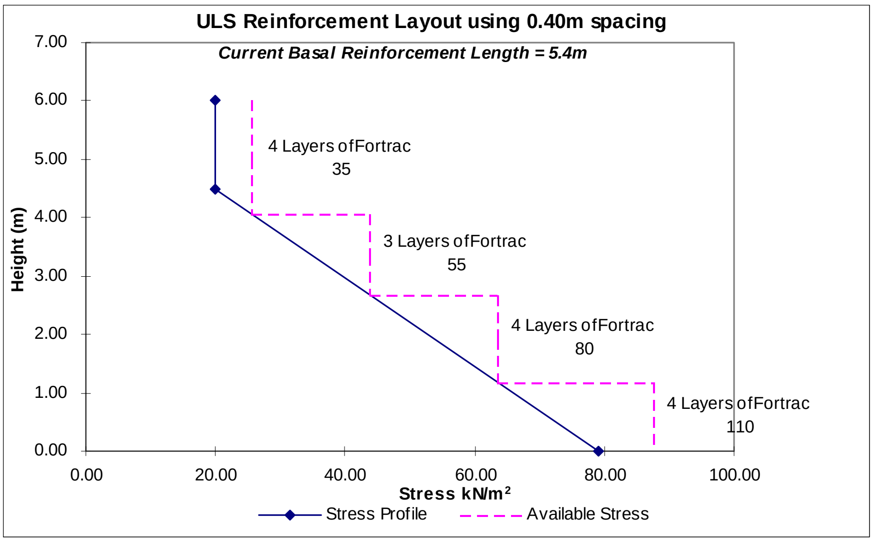

Figure 2: Graphical Output from the Design Spreadsheet

As the sources of the fill for the reinforced soil embankments and its properties had not been identified the detailed designs were prepared using three values for the shear strength and three different values for the bulk density, which when combined gave nine designs for each of the design heights of embankment. The parameters were chosen to span the full range of each characteristic that could be expected for soils to be used in the works. The design heights were 1m, 2m, 3m, 4m, 5m, 6m, and 7m. The design parameters used are given in Table 1.

The design height was defined from 500 mm below the finished ground level to allow for the excavations for the face vegetation.

Table 1. Design Parameter used for Reinforced Soil Embankments**.**

Parameter	Values used in analysis
Bulk Density (t/m^3)	1.9, 2. and 2.1
Shear Strength (φ' degrees)	30, 35, 40

The final design cross section is shown in Figure 3

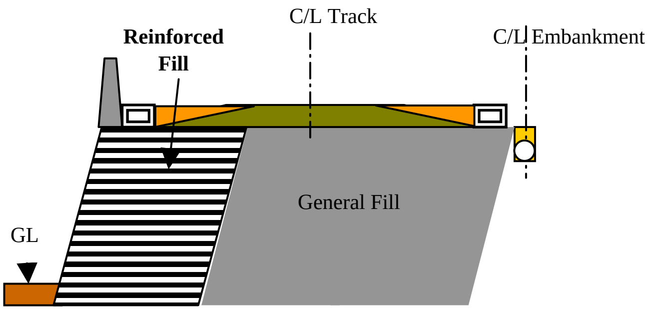

Figure 3: Typical Section of Reinforced Embankments

Once the sources of fill had been finalised, laboratory tests to measure the characteristics in Table 2 were carried out to determine which of the nine designs for the geogrid layout should be used on site for construction

Table 2: Results of Tests on Soils used in the Reinforced Fill

Characteristic	Design Value	Value from tests on fills used in the works, mean (range)
Bulk density (γ_b) (t/m^3)	2.0	1.99 (1.92 min) (2.02 mean)
Shear strength (300mm shear box) (ϕ') (degrees)	30	35° (31.4° min) (37° mean)
Geosynthetic to soil interaction coefficient (f_{ds})	0.6	0.95 (0.85)
Particle size distribution	SHW (ref. 4) Class 6I or 6J	Restricted grading within limits for Class 6I

The reinforcement arrangements for each of the design heights are set out in Table 3. All sections were built with the geogrid reinforcement set to a constant vertical spacing of 0,4m.

Table 3: Reinforcement layouts

Design Height (m)	Reinforcement Type & number of layers @ 0.4m centres) (Characteristic Strength kN/m)		Length of reinforcement (m) (BS8006 min 3,0m)
1,0	35	1	3,0
	55	2	
2,0	35	2	3,4
	55	3	
3,0	35	3	4.3
	55	3	
	80	2	
4,0	35	3	5,2
	55	3	
	80	2	
5,0	35	4	6,1
	55	3	
	80	4	
	110	2	

6,0	35	4	7,0
	55	3	
	80	4	
	110	4	
7,0	35	6	7,9
	55	4	
	80	5	
	110	5	

4 CONSTRUCTION OF THE REINFORCED EMBANKMENTS

Construction of the works started in June 1998, with site clearance and preparation of the formation, including the removal and replacement of any soft spots just prior to the placing of the bottom layers of the geogrid reinforcement.

The galvanised facing units were held at the correct face angle using timber supports, a heavy (300 g/m^2) special UV-stabilized non-woven needle punched geotextile was placed between the geogrid and the galvanised facings. The geotextile was used to give some protection from UV radiation to the geogrid until vegetation could be established. A layer of topsoil was placed behind the geogrid and then the granular fill was compacted in layers up to the level of the next layer of geogrid. This process was repeated up to the top of the embankment and is shown in Figure 4.

Figure 4. Construction of reinforced fill and facing

At the top of the reinforced soil embankments a parapet is formed using the same galvanised steel mesh as is used for the facing but filled with 100mm to 150mm crushed rock. The section of the parapet can be seen in Figure 5.

Figure 5 . Green Corner and Parapet in Reinforced Soil

At the end of the reinforced soil embankments run up to the abutments of the stations or the viaduct sections. The architect required that the reinforced soil overlapped the reinforced concrete structure, to form a 'green' corner to the structures. Prefabricated corner elements were specially produced to form sharp edges to the green corners. The connections to the concrete structure were ensured using expanding stainless steel bolts fastened into the concrete structure and further connected to the galvanised steel mesh. A 100 x 100 mm rolled steel angle section was fastened to the concrete structure to form at flexible connection to the concrete structure, which also hides any differential settlements or facing deformations between the two parts of the structure.

The development of the detailed design of these features was not straightforward and they were not easy to construct on site, Figure 5 shows one of the completed 'green' corners.

The soil to be used in the reinforced parts of the embankments was originally intended to be partly sourced from suitable granular arising from the excavations at other parts of the works. This was not possible due to programme constraints and all the granular fill required was sourced from offsite. For the embankment core, it was originally intended that much of this would be provided from lightly contaminated fill that was excavated from other parts of the works. The use of lightly contaminated soil in the core of the embankments was considered to be an environmentally sound way of disposing of the material, rather taking it to a landfill offsite. The pollutants in the soil were intended to slowly degrade in the core of the embankment and extensive numerical modeling was carried out to look at the infiltration of rainwater through the embankment, together with the transport and degrading of the pollutants. From this modeling, a detailed risk analysis was prepared which showed that no unacceptable environmental risks were caused. Detailed discussions were entered into with the authorities regarding the use of this slightly contaminated soil in the embankments. These discussions resulted in an appeal being lodged with the Danish Environmental Protection Agency regarding the conditions imposed by the authorities. It was not possible to resolve this matter with the authorities in sufficient time and in order to progress construction, clean granular fill sourced from offsite was used for the core of the embankments.

The use of granular fill in the core of the embankments, rather than the general fill as originally intended had other effects on the construction. The granular fill was less sensitive to moisture content variations and could be placed in most weather.

5 PERFORMANCE OF THE REINFORCED SOIL EMBANKMENTS

During and after construction, monitoring was carried out to determine deformation of the face of the reinforced embankments together with measurement of vertical settlement of the embankments. Deformation measurements of the face showed very little movement post construction, with less than 10mm of movement being observed. This was also the case for the settlement monitoring, with only a few millimeters being observed post construction. These small movements are considered to be due to the use of the granular fill materials and good practice with regard to compaction. Use of the mesh facing as formwork, has resulted in small construction tolerances being achieved and a good visual appearance of the embankments. The result is in keeping with the architectural appearance of the other elements of the above ground works and has closely respected the architect's vision.

6 CONCLUSIONS.

The reinforced soil embankments required for this project are now complete and track laying has been carried out over these sections. Trial running of the Metro trains has already started in this section and the Metro is due to open to passenger traffic in 2002.

The embankments have so far shown only very limited deformation and have performed as intended and predicted in the designs. The construction of them has gone as planned and the use of the mesh facing system as formwork has proved to a very effective system for achieving a high standard of finish to be achieved. It has not unfortunately been possible to use lightly polluted soil from the excavations elsewhere on the project, although the use of imported granular fill has enabled the construction to take place with less dependency on the weather.

ACKNOWLEDGEMENTS

This paper has been prepared by three authors who have worked directly and closely with this aspect of the project, we would like to thank our respective employers for their permission to prepare and publish this work. Additionally we would like to acknowledge the permission of the project client Ørestadsselskabet publish this paper.

The Comet joint venture is lead by ny Carillion, other partners in the joint venture are Bachy Soletanche, SAE, Ilbau, Astaldi and NCC. The Joint Venture's civils designer is Maunsell Ltd. Byggros are the sub-contractor for the design and supply of the reinforced soil elements.

REFERENCES

ENV 1997 – 1, 1995, Geotechnical Design CEN.

BS 8006: 1995 Strengthened Earthworks

Jewell R J ' Revised Design Charts' Proceedings of the Symposium on Reinforced Soil, Cambridge, 1994 Thomas Telford Ltd.

BBA Certificate No 97/RO96 Fotrac Geogrids, British Board of Agrément.