Embarkment stabilisation works between Rayners Lane and South Harrow Underground stations

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Introduction

In January 1863 the world’s first underground railway opened in London. Initially 6km long, it ran between Paddington and Farringdon Street. Today around 500 million people travel on London Underground every year. The network covers 382 route km of track with 228 km on the surface. There are approximately 238 linear km of earth structures on the surface railway equally split between cuttings and embankments. Up until the mid-1990s disruptive slope failures occurred across the network with rising track and earth structure maintenance requirements often resulting in the imposition of speed restrictions.

It is London Underground’s (LUL) policy to enhance and modernise the network by improving its infrastructure to an extent where it is “invisible” to the customer. In order to upgrade the earth structure assets and decrease the existing frequency of costly track maintenance, LUL has prioritised locations requiring remedial works. The stabilisation of Rayners Lane to South Harrow embankment formed part of the LUL Earth Structures Project (ESP). LUL established the ESP in 1992 to inspect, investigate, assess design and implement stabilisation works at locations where deformation of the earth structure was having a detrimental effect on track and ride quality resulting in speed restrictions and service delays.

Rayners Lane to South Harrow embankment provides support to both sides of the railway track over a distance of 200m and rises up to 9m in height. The embankment is designed to ensure a smooth transition with the South Harrow viaduct. Kværner Cementation Foundations was awarded the design and construction of the stabilisation works in January 1998, following an investigation and slope stability assessment undertaken by the ESP [5]. The embankment was heavily vegetated with...
mature trees (Figure 1). As in any type of civil engineering work undertaken in a highly urbanised area, it was anticipated that local residents would take a keen interest in the stabilisation works.

This paper describes these specialist ground engineering works and comments on the behaviour of the embankment after a year of post-construction monitoring.

History of Rayners Lane embankment
At the end of the 19th century, and typical of many of LUL embankments, Rayners Lane was constructed from London Clay taken from adjacent cuttings. The clay was generally side-tipped from railway wagons with little or no compaction. Failures were known to have occurred in these clay embankments during construction predominantly when height reached around 6m or 7m. These were often repaired using granular materials or locomotive ash and the slope angles adjusted on the basis of ongoing experience. Since the line opened to traffic in 1994, time, seasonal movement induced by vegetation controlled shrink/swell, slope geometry and the intermittent dynamic loading from the passage of trains have led to overstress embankment slopes and shoulders. In 1971, both sides of the embankment were grouted to prevent further settlement of the track but the improvement was at best temporary.

Deterioration of the earth structure and track continued and 25 years later evidence of instability was in various forms (Figure 2).

These visual observations are the result of three deformation mechanisms summarised as A, B, C on Figure 2. A is a deep-seated slope failure, B is a shallow shoulder instability problem (shoulders are chiefly made of ash), and C is the seasonal shrinking and swelling of the embankment fill. All of these deformation mechanisms resulted in unacceptable track quality. With seasonal vertical track movements of ±50mm being recorded particularly close to the viaduct. This resulted in a track speed restriction of 32km/h being imposed over the site.

The solution to Rayners Lane embankment
In order to improve embankment stability and to provide an adequate lateral support to the track, various stabilisation measures were designed by Kvaerner Cementation Foundations' subcontract designer Mott MacDonald (Figure 3). A factor of safety of greater than 1.3 was designed against failure of the embankment, for either deep seated or shallow slope failure. The design life of 120 years is the solution was combined to allow a steady increase in stiffness of the stabilisation solution as the embankment approached the viaduct, to reduce the current embankment deformation and to restrict longitudinal differential track movement to the contract requirements of ±20mm over any 10m length of track.\(^{6}\)

The site plan illustrates how confined was the access on the embankment slopes, especially to the north where works were carried out very close to adjacent properties. Liaison with residents was very important to explain the various phases of the works. To carry out the piling and earthworks, vegetation was cleared. The decision to keep or remove some of the trees that minimised the impact of passing trains on adjacent properties was made in conjunction with LUL Environmental Manager. Part of the works scope also included the re-vegetation of the slopes with a planting scheme designed to minimise the long term shrink/swell of the embankment.

The hard solution – the retaining wall structure
Where the height of the embankment exceeded approximately 6m a bored pile retaining wall was constructed. As shown on Figure 4 (section AA on Figure 3) the vertical and raking piles penetrated all potential slip failures which caused deformation to the lineside services and local movements to the track.

Mini-piles were bored using rotary piling rigs, operating perpendicular to the track (Figure 5). Spaced at regular intervals, piles were founded in the insitu material, the London Clay. Support against lateral earth pressure was provided by 310mm diameter raking piles working in tension. The arrangement of the piles consisted of 8.5m long vertical piles and 11.5m long raking piles, on each side of the embankment. Capping beams encased the top of the bored piles and acted to tie the piles together. These beams were designed to resist the loads from the backfill material and transmit the load to the raking piles. The height of the wall reached the steeper level to ensure that the backfill provided adequate lateral support to the track and lineside services, thus solving the shallow shoulder stability problems and offering a safe walkway for track personnel (Figure 7).

The wall was not visible from passing trains and screening with suitable vegetation species was designed to reduce its impact on adjacent properties.

The soft solution – the new earth structure
As the height of the embankment reduced, slope stability analyses indicated that a bored pile wall was not required beyond 60m west of the viaduct. Granular fill material was imported and placed and compacted in layers on the embankment in order to regrade the side slopes to a shallower angle. The method of compaction was in accordance with Method 2 of the Specification for Highway Works. An independent laboratory regularly controlled the quality of the earthworks by means of nuclear density testing and soil laboratory testing. Figure 6 (section BB on Figure 3), shows the different slope geometry used to fit in the available space.

On the eastbound elevation the design solution also included a reinforced earth wall structure over a 71m length beyond the end of the piled retaining wall. This was the first time Kvaerner Cementation Foundations had used this technique and compared to gabion baskets, a reinforced earth wall offered an aesthetically attractive appearance as it allowed grass to be grown on 45° slopes. Feedback from the local residents showed that they were satisfied with this invisible toe wall (Figure 7). Structurally, the reinforced earth retaining wall also provided additional toe weighting thus improving the stability of the embankment slopes. A reinforced earth retaining wall is economic to construct and has a lower installation risk provided weather conditions are favourable, as in any type of earthworks.

Along with the earthworks construction, a 400m length of toe drainage was also completed to allow the toe of the embankment to drain (Figure 6). The installation of this drain also benefited local residents to the north since their back gardens used to flood after heavy rainfall.

Instrumentation of the embankment
In order to demonstrate the efficiency of the stabilisation works a number of monitoring instruments were installed. As the works progressed, new piezometers, inclinometers and strain gauges were installed and base readings taken as early as practicable in the contract.

The instrumentation allowed the behaviour of the embankment and the track to be monitored throughout the contract.

Variations of the groundwater table in the embankment were recorded using standpipe piezometers. As expected the phreatic surface remained below the tip of all the standpipe piezometers since the pore pressures near the embankment surface were known to be suctional due to the influence of the existing vegetation.

The horizontal separation between the concrete piled retaining walls was monitored by installing inclinometers in four of the vertical mini-piles. The maximum horizontal displacement was in the order of 7mm in the 12 months post construction monitoring period and located at the
The effect of the trees on the embankment was evident from the recorded deformations. The trees caused significant movements, with the maximum recorded being 3% of the elastic limit of T32 steel bar. The instrumentation of the bored pile retaining wall has shown excellent results with minimal deformation being recorded. The track levelling has indicated some movements which have been cross-referenced to the influence of mature trees located relatively close to the track. Although the stabilisation works have improved the stability of the railway embankment to an acceptable factor of safety, further monitoring is required to determine whether the observed track deformation is acceptable in the long term.

**Behaviour of Rayners Lane embankment**

Vertical movements of the eastbound and westbound tracks were recorded using a rail levelling technique. This is a simple and reliable method to assess the overall achievement of the contract deformation and differential settlement criteria of the tracks. Before the works started base readings were taken every 5m along the rails over the 200m length of the embankment. Figure 8 shows the movement of the eastbound outer rail during the construction period, from January 1998 to May 1998.

The eastbound outer running rail underwent maximum vertical movements of ±10mm at the bored pile wall position, whereas the new earthwork structure showed maximum vertical movements of ±10mm and, in both cases, over more than 10m of track. These movements are perfectly acceptable since they remain within the contract differential settlement criteria of ±20mm over 10m of track. However, during the period that followed the end of the construction, significant vertical track movements took place, as shown on Figure 9. Looking at the track monitoring results, it became evident that the movements occurred during the summer period and in the same area, i.e., over the earthworks section and not over the bored piled retaining wall section.

The different stiffness of the two structures causing such movements? By cross-reference on site, it was established that the actual peaks on the graphs corresponded exactly to the positions of the mature trees that had remained on the embankment slope. The trees growing on the embankment enhanced the seasonal shrinking and swelling of the underlying clay fill. During the summer period, trees absorb significant amounts of moisture in the embankment clay fill. Even if the trees slow down their growth, the underlying clay does not have time to rehydrate to its original level of moisture and remains desiccated. Thus, trees progressively induce additional settlement to the tracks every summer.

Environmentally, it was contentious to remove the trees close to the track as it would virtually eliminate all vegetation left on the embankment and would be resisted by the local residents. The question however remains, what should be done to prevent these seasonal settlements? Further research will be carried out by Imperial College to monitor the seasonal variations of pore pressure at selected locations in the embankment in order to determine the most influential trees. Mott MacDonald will then incorporate this data into a numerical analysis to allow a more informed judgment of the position of trees which can be left in place to minimise their detrimental effect on the track.

On examination of the results, at the end of the contract defects liability period in late 1999, an agreement will need to be reached between London Underground Limited and Kvaerner Cementation Foundations, following consultation with local residents. Either the trees will be left and the future track deformation accepted or if the deformation is considered unacceptable the trees will be removed and replaced by an acceptable planting scheme consisting of relatively low water demand vegetation species.

**Conclusions**

The instrumentation is not only useful to demonstrate the satisfactory completion of the works, it is also fundamental to understand how the retention of trees close to the track affects the performance of the embankment and the track.

The instrumentation of the bored pile retaining wall has shown excellent results with minimal deformation being recorded. However, the track levelling has indicated some movements which have been cross-referenced to the influence of mature trees located relatively close to the track. Although the stabilisation works have improved the stability of the railway embankment to an acceptable factor of safety, further monitoring is required to determine whether the observed track deformation is acceptable in the long term. The new embankment planting scheme has been designed to minimise shrink-swell of the embankment clay fill and provides a suitable screening from adjacent properties. It will also allow in due course allow the removal of the existing mature trees if the ongoing monitoring reveals their effect on track quality to be unacceptable.

In addition to finishing on time and within budget, Kvaerner Cementation Foundations' work procedures and organisation have added value to the construction process. Innovation in the construction of geotechnical works has brought economic (reinforced earth wall), practical (control of earthworks by nuclear density testing, use of laser level) and time benefits (inclinometers and strain gauges readings, precise levelling) to the project, as well as reducing the risk of a slope failure, eliminating a speed restriction and reducing maintenance costs to LUL.

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**References**