COST EFFECTIVE DESIGN AND CONSTRUCTION OF EMBANKMENT STABILISATION SCHEMES TO A PERFORMANCE SPECIFICATION

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ABSTRACT
The management of existing rail infrastructure to prolong lifetime and reduce maintenance cost and disruption is clearly recognised as a vital part of railway management. Aspects of the design, construction and performance of some 8500m of rail embankment stabilisation works carried out for London Underground Ltd are presented in this paper.

The works have been designed and built by Keller Ground Engineering to tight performance criteria specified by London Underground for a Design Life of 120 years. Particular emphasis is placed on the effectiveness of a number of different stabilisation methods in reducing track movements, illustrated by the presentation of data obtained from extensive monitoring of the structures since construction. Conclusions are drawn from the wide experience gained in this type of work linking the cost effectiveness of stabilisation methods to their effectiveness in meeting the required performance criteria.

INTRODUCTION

The London Underground network includes some 400km of surface railway of which approximately 100km run on earth embankment,, much of which is over 70 years old. Typically, the embankments were built up from natural materials (mostly from adjacent cuttings) by end tipping directly onto the in situ soils with little or no compaction. Consequently, since construction, large deformations have occurred in many of the structures and to maintain track levels, placement of locomotive ash, clinker and ballast was undertaken. Deformation and failures continue to occur in the embankments, which require extensive and costly maintenance to maintain satisfactory track quality. Figure 1a illustrates a typical embankment cross section showing the cohesive fill core with ash/clinker capping overlying the in situ soils.

A number of deformation mechanisms characterise these embankments including:

- irrecoverable ravelling of the over-steepened ash fill under dynamic loading from passing trains, particularly over the dry summer months;
- seasonal shrinkage and swelling, typically about ± 50mm, which is strongly influenced by vegetation, and results in gradual spreading of the embankment side slopes towards the natural angle of repose of the fill material;
- deep seated rotational slip failure, frequently precipitated by sudden rise in pore water pressures.

As part of the ongoing maintenance of these embankments, a stabilisation programme has been implemented by London Underground Ltd (LUL) aimed at reducing track and rolling stock maintenance costs and improving track ride quality. This paper illustrates a number of such stabilisation packages designed and built by Keller Ground Engineering (KGE). These packages were let after competitive tender, on the basis of the proposed schemes' ability to reduce track deformation as outlined in the Contract Performance Specification.

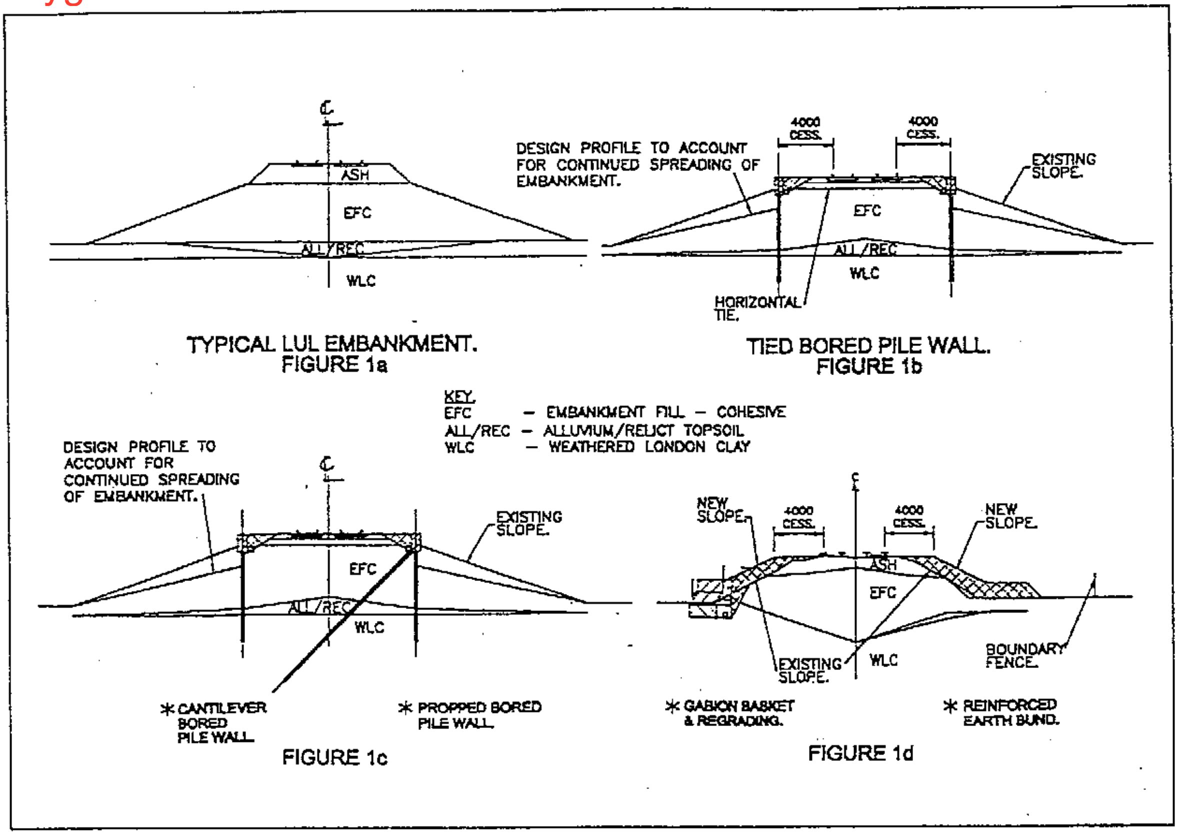

Figure 1
Typical sections through London Underground embankments showing various stabilisation schemes

THE PERFORMANCE SPECIFICATION

From a Client's perspective, requiring the contractor to produce a scheme that will achieve a given performance offers the greatest possible scope for cost effective design and construction. The LUL Performance Specification to which the schemes presented have been constructed may be summarised as:

- Design Life of 120 years with construction in accordance with LUL Engineering Standards;
- Limit to embankment deformation to enable achievement of track maintenance targets of
  - vertical rail position: -20mm +15mm
  - lateral rail position: ± 9mm
  - rail cross level: -15mm +10mm
- to improve stability of embankment to give a minimum 1.3 factor of safety on soil strength.

The overall scope of the individual stabilisation schemes was defined by LUL who also provided factual and interpretative geotechnical reports quantifying the condition of the embankments. For each stabilisation scheme KGE then developed an overall design and construction package to meet the criteria set out in the Contract Performance Specification.

Significant reductions in cost per metre of embankment stabilised have been achieved over time as shown in Figure 2. These cost reductions are attributed to:

- the establishment by KGE of "standard" designs, management structures and working practices (accruing the benefit of climbing a single learning curve for a number of projects);
- the increased productivity and safety awareness of a well trained work force;
- continual refinement of existing practices and design, facilitated by observation of the performance of completed structures.
- improvement in the supply chain through development of continuity, with sub-contractors and suppliers becoming more familiar with KGE/LUL requirements.

Interestingly enough, Figure 2 shows a cost reduction per metre of embankment stabilised of around 40%, which is in excess of the much quoted figure of 30% suggested by the Latham report, and there is every reason to believe that similar cost efficiencies could be expected to accrue from the application of the principles underlying the development of similar package works to a Performance Specification in other construction fields, whether associated to railway works or more general applications.

It is clear that the successful integration of the design, management of construction and performance monitoring functions has contributed to the efficient completion of the stabilisation schemes constructed to date. Each of these functions is covered briefly below.

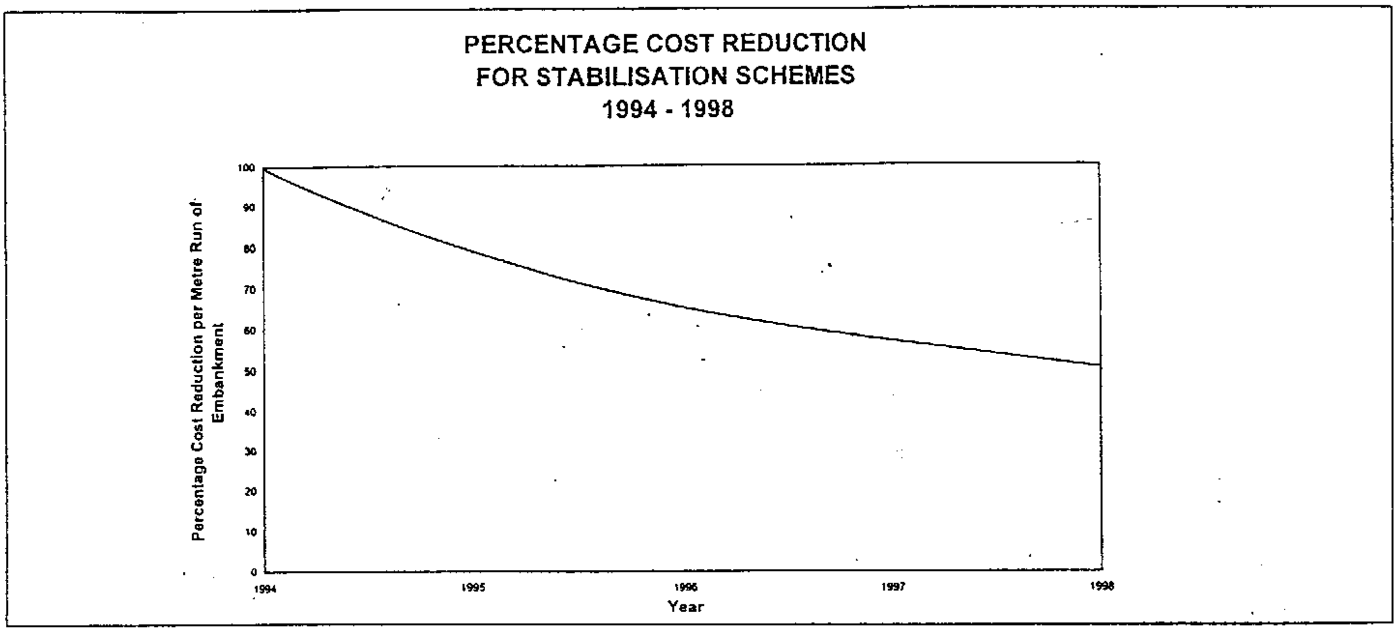

Figure 2
Relative cost reduction per metre of stabilised embankment 1994 to 1998

DESIGN
A number of embankment stabilisation options illustrated in Figure 1 have been developed and have proved to be both versatile and cost effective:

- structural contiguous minipile wall (tied, propped and cantilever) with capping beam;
- reinforced earth bunds;
- gabion retaining walls.

To date KGE have undertaken the design and construction of embankment stabilisation schemes over nearly 8.5km of the LUL above ground infrastructure. The extent of the various options outlined above are summarised in Table 1.

Type of Solution	Embankment Length (m)
Structural Wall	7120
Reinforced Earth Bund	1000
Gabion Wall	380

Table 1

Structural Contiguous Minipile Wall
This solution is compact, and is particularly useful for the highest embankments and where pre-existing slips are known to exist. The piled wall is constructed to sufficient depth to ensure potential slip planes are intersected by a structural member. Restraint is provided at the over steepened embankment shoulder by a structural capping beam which allows the construction of a 4m wide cess and provides a convenient location for cable runs. A reduction in support down slope of the wall is incorporated in the design which ensures that further spreading of the embankment toe over the 120 year design life of the structure can be accommodated without resulting in excessive wall deflection affecting the line and level of the track. Where there is a minipile wall on each side of the embankment, horizontal ties provide an effective means of controlling lateral deflections; where this is not the case, raking tension piles may be used. For lower embankment heights, cantilever piles have been used, however, deflection criteria usually govern their adoption rather than their structural capacity to stabilise the slope.

Reinforced Earth
To date some 1000m length of embankment has been stabilised using reinforced earth and regrading (shown in Figure 1d). Shoulder restraint is provided by the addition of material at the top of the slope to form a 4m wide cess and a larger bund is constructed to provide extra weight at the toe of the slope to enhance the factor of safety against deep seated slips to in excess of 1.3. While this approach has proved highly cost effective, it does however require sufficient room at the embankment toe and is therefore not appropriate in all cases.

Gabion Retaining Walls
For embankments of low to moderate height, placement of imported engineering fill over the side slopes and retained at the toe behind gabion basket retaining walls, (shown in Figure 1d), has proved an appropriate option providing sufficient toe space is available.

Drainage and Vegetation
The control of groundwater is a key issue whatever stabilisation scheme is adopted, and therefore the provision of adequate drainage and suitable vegetation forms a core part of each of the stabilisation schemes. The provision of suitable vegetation must reconcile a number of conflicting requirements [Gellatley et al, 1994]. On the one hand mature vegetation provides an attractive visual and acoustic barrier to the lines, yet on the other hand excessive leaf fall can affect train services, particularly in the autumn, and the seasonal variation in water demand is thought to contribute significantly to a seasonal shrink/swell cycle in the clay core. The integrated design of stabilisation schemes enables the balance of all of these aspects to be controlled.

MANAGEMENT OF CONSTRUCTION
The embankment stabilisation schemes completed by KGE have been typified by a number of logistical difficulties presented by the nature and location of the embankments within the local environment. These logistical problems are characterised by the following:

- stabilisation works being carried out without disruption to the operation of the railway.
- difficult access onto the site – steep, heavily vegetated slopes with a narrow operating width;
- initial instability of the embankment sides.

Throughout the involvement of KGE in the stabilisation packages, it has become apparent that the development of 'production' type elements for different stabilisation schemes has been of great benefit. Furthermore the use of 'standardised' design solutions for particular applications, together with the ongoing involvement of a 'core' team of personnel, both office and site based has allowed a substantial decrease in approval periods for design, safety, quality and environmental plans.

The adoption of light weight drilling rigs operating off relatively narrow scaffold platforms located adjacent to the crest of the embankment: contribute to the success of the packages by ensuring the already marginal stability of the embankments are not impaired (see Figure 3). By utilising the cable run as a permanent barrier to the track side services ensures that normal operation of the railway can continue during the works. The installation of the piles leads to immediate increase in the resistance of the embankment to instability.

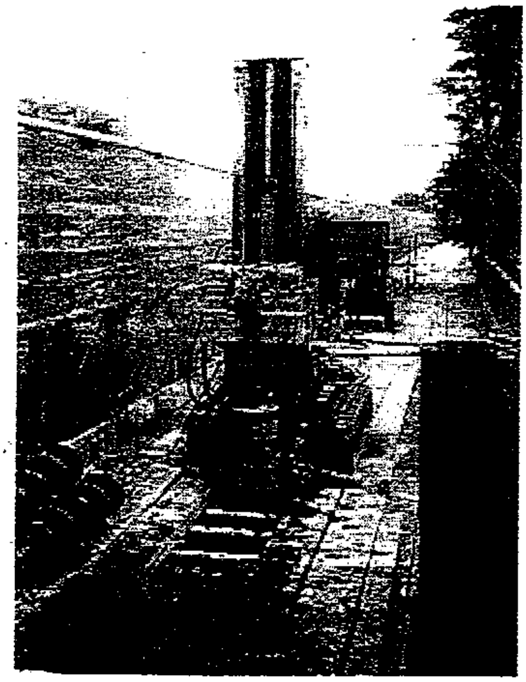

Figure 3
The use of lightweight plant working adjacent to railway lines

In all cases, KGE have undertaken the role of Principal Contractor under the CDM Regulations, all works being performed under site specific safety and quality plans approved by LUL . The contribution to the overall success of the stabilisation packages resulting from the implementation of suitable controls for safety and quality, which are fundamental to the safe operation of the sites within the environment of the operating railway, cannot be over-emphasised.

These controls cover:

- the initial detailed site survey to allow detailed design;
- site clearance of vegetation and mature trees to accommodate installation of access and temporary scaffold platforms;
- installation of the bored minipile wall , incorporating RC beam;
- construction of drainage, both at the crest of the embankment and at the toe of the embankment;
- re-vegetation of the embankment side;
- post construction monitoring of the structures.

PERFORMANCE
Since construction, a number of the minipile structures have been monitored to assess their performance. Examples from two sites (one a cantilever wall, the other a tied wall) are given below. To date insufficient monitoring has been carried out on reinforced earth or gabion basket stabilisation scheme to allow comment on achieved performance.

<u>Cantilever Wall</u>
Figure 4 compares the predicted and actual movement of the top of a cantilever bored minipile wall constructed in 1997 as part of the Barkingside to Fairlop Phase II works on the Central Line in North East London. The wall comprised minipiles installed at 650mm centres to an embankment approximately 4.5m in height.

The movement of the wall was derived as follows:

- Predicted movement: carried out at design stage using FREW (Oasys Ltd, 1991).
- Apparent movement: measurement made by inclinometer placed at the rear of the reinforced concrete beam.

The FREW analysis comprises a soil structure interaction modelling of a flexible retaining wall, allowing prediction of ground movement at varying stages of a construction sequence, with varying soil properties and groundwater models.

At the design stage the analysis comprised a 'serviceability' model of the retaining minipile wall.

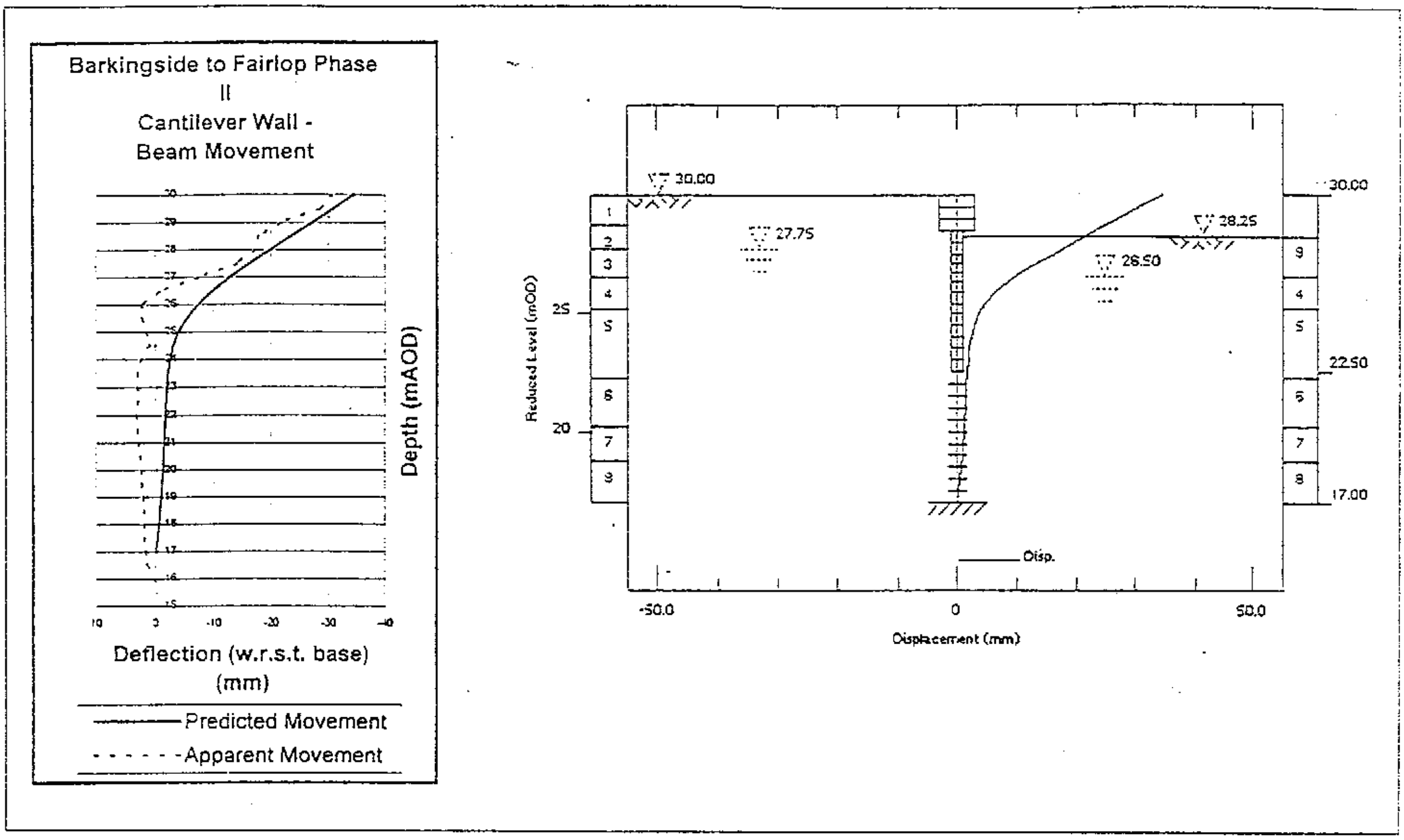

Figure 4
Comparison of measured and predicted cantilevered bored minipile wall deflections with depth

Tied Wall

Figure 5 shows the movement of the top of the wall at one location for a tied bored minipile wall constructed in 1996 as part of the Burnt Oak to Collingdale Phase II stabilisation works. The wall comprised minipiles at 450mm centres with horizontal ties every 4.5m, stabilising an embankment 8.0m high. The apparent movement of the top of the wall was derived by three independent methods:

- optical surveying to measure the relative outward horizontal displacement of the monitoring studs located on the top of the capping beams;
- measurements from inclinometers placed in the cess:
- monitoring of vibrating wire strain gauges bonded to selected horizontal ties.

The data, which is typical of that measured elsewhere on the structures, indicates that a "bedding in" period of approximately 6 months followed the effective completion of construction. Curiously, one inclinometer recorded a movement of a 4mm inward movement towards the track. A similar response was recorded in a total of three out of nine inclinometers; as yet no rational explanation of this apparent behaviour has been confirmed.

Following the "bedding in" period, the strain gauge data, shown in Figure 6 indicates a sensibly constant value which equates to a mobilised tie load of approximately 50kN. The inclinometers have both shown further small outward movement. Continued monitoring is required to verify whether the wall deflections have reached their long term serviceability level or are continuing.

It has been suggested [Vaughan 1997] that the loads in the ties might exhibit a gradual rise over their lifetime due to a ratcheting up of the lateral confining pressures on the active sides of the walls, resulting from the seasonal shrink/swell cycle of the embankment clay core. Although this mechanism is yet to be universally accepted, the ties may be constructed with de-stressable heads that will allow future monitoring and if necessary load release should the ultimate design capacity of 200kN be approached.

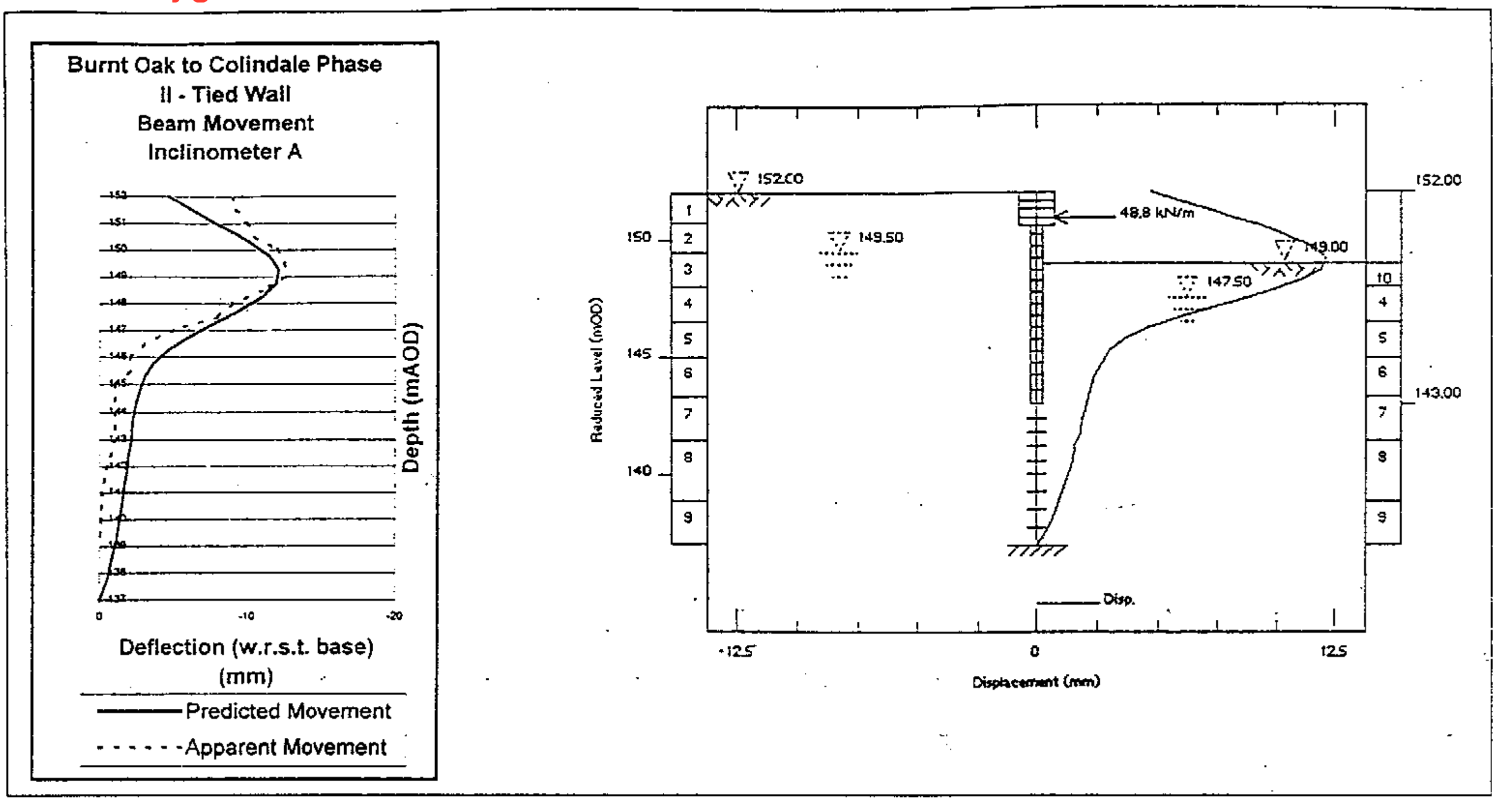

Figure 5
Comparison of measured and predicted tied minipile wall deflections with depth

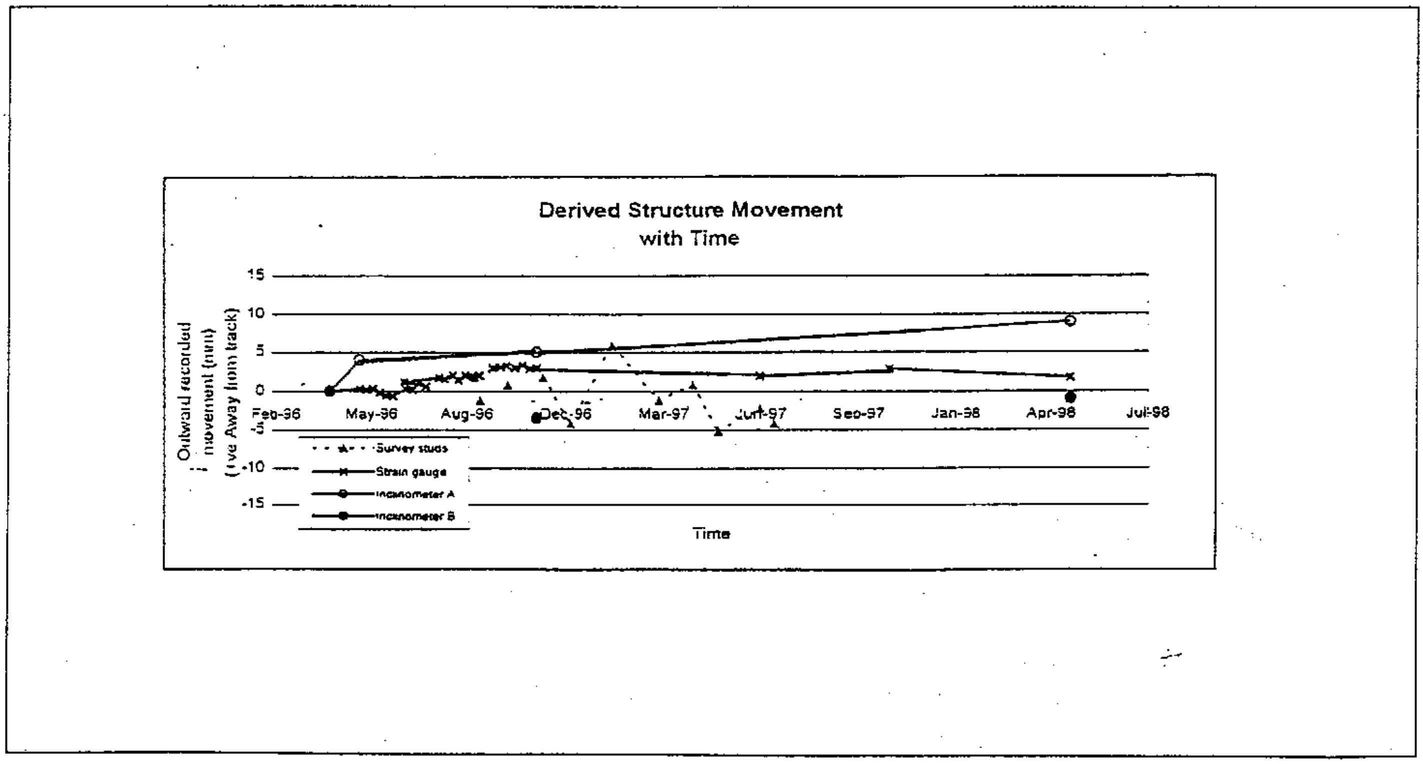

Figure 6
Derived movement of the top of a tied bored minipile wall

CONCLUSIONS

Throughout the remediation of some 8500m of rail embankment for London Underground Ltd., Keller Ground Engineering has demonstrated the cost effectiveness of the application of an integrated design and construction approach to the stabilisation works packages.

The demonstration of a significant overall cost reduction in terms of cost per metre of embankment stabilised over a 4 year period is attributed to the experience brought to the project incorporating a wide range of construction activities in to the projects.

Extensive post construction monitoring of structures has not only substantiated the original design models but has enabled a continual refinement of existing design and construction practice.

It is apparent that a review of completed track monitoring identifies a significant reduction of rail deformation thus ensuring an improvement in overall ride quality and hence reduction in track maintenance.

The case studies from the schemes outlined in the paper demonstrate that within a suitable contractual and physical environment an integrated design and construction package can offer significant cost savings whilst maintaining the safety of the railway, the quality of the finished product and its future satisfactory performance.

ACKNOWLEDGEMENTS

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