EARTHWORKS MANAGEMENT
THE DISADVANTAGES OF DESIGNING TO A BLANKET FACTOR OF SAFETY

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ABSTRACT
Approximately 10,000km of the UK's rail network is either runs on or is contained in earthworks that were constructed around 150 years ago. Construction standards and methods were significantly poorer than they are today and the discipline of Geotechnics had yet to be invented. Yet today we face the challenge of maintaining and running a modern and reliable rail network on and through many earthworks that do not pass modern design standards.

The design standards used in the design of remedial measures are often based on concepts of achieving a blanket improvement in prescribed factors of the earthworks most of which, by definition, were constructed with a factor of safety of unity. In many instances this leads to extensive and expensive remedial measures. Seeking to realise cost savings in the process of managing earthwork assets without revisiting the fundamental basis of current design methods to move away from overly prescriptive factor of safety requirements and replacing this with a greater emphasis on performance requirements restricts the opportunity of the designer and client to generate the maximum impact from minimum cost.

This paper will challenge the paradigm whereby greatest reliance is placed on achieving a prescriptive factor of safety in the design of remedial earthwork measures while actual earthwork performance appears to be understood only as a secondary issue. An approach is suggested where the performance requirements of the track supported or contained by the earthwork becomes the key design criteria.

1.0 INTRODUCTION

The majority of the UK's mainline rail network with its associated earthworks was constructed between 1830 and the end of the nineteenth century, before the discipline of Geotechnics had developed. The earthworks were built by hand, following crude empirical rules, by navies who were paid on the tonnage of material shifted per day and contractors who made their money by building as much as they could as quickly as they could. By today's more enlightened standards the quality of construction would be considered inadequate and in fact many earthworks do not perform as required in today's operating environment. Today we face the challenge of maintaining the legacy of this period of frenzied construction activity.

Where poor earthwork performance reaches critical levels remedial works are usually implemented in accordance with the infrastructure owner's relevant specifications. These specifications usually set out the standard, amongst other things, for the design of remedial works to embankments and cuttings.

These specifications usually encapsulate and build on the practice of designing earthwork remediation schemes primarily based on achieving a minimum prescribed factor of safety for the remediated earthwork. In practice this approach requires that the Ultimate Limit State failure of, through or beneath the earthwork will be prevented. This is done by ensuring there are no potential failure surfaces with a factor of safety on soil strength of less than the prescribed value (typically 1.3 using moderately conservative design parameters). Figure 1 shows the concept in terms of an embankment. Additionally performance criteria may be stipulated. Table 1 shows the allowable cess settlement following construction of the works from the Network Rail specification.

Time after re-opening to rail traffic following end of construction.	**Maximum permitted settlement after re-opening to rail traffic (measured at survey monuments in cess).**
4 Weeks	15mm
6 Months	25mm
12 Months	30mm

Table 1 Settlement limits for earthworks schemes from RT/CE/S/071 (2004)

Design validation is usually demonstrated by undertaking limit equilibrium slope stability calculations to achieve a given factor of safety.

A key point to note is that in practice the specifications are often interpreted as requiring that all of the possible failure surfaces (for which those labelled (a) to (d) in Figure 1 form a sub-set) must achieve the minimum factor of safety. This will be termed the Blanket Factor of Safety Approach because no differentiation is made between the value of the required factor of safety for failures affecting different parts of the structure (as shown by the three failure classes in Figure 1).

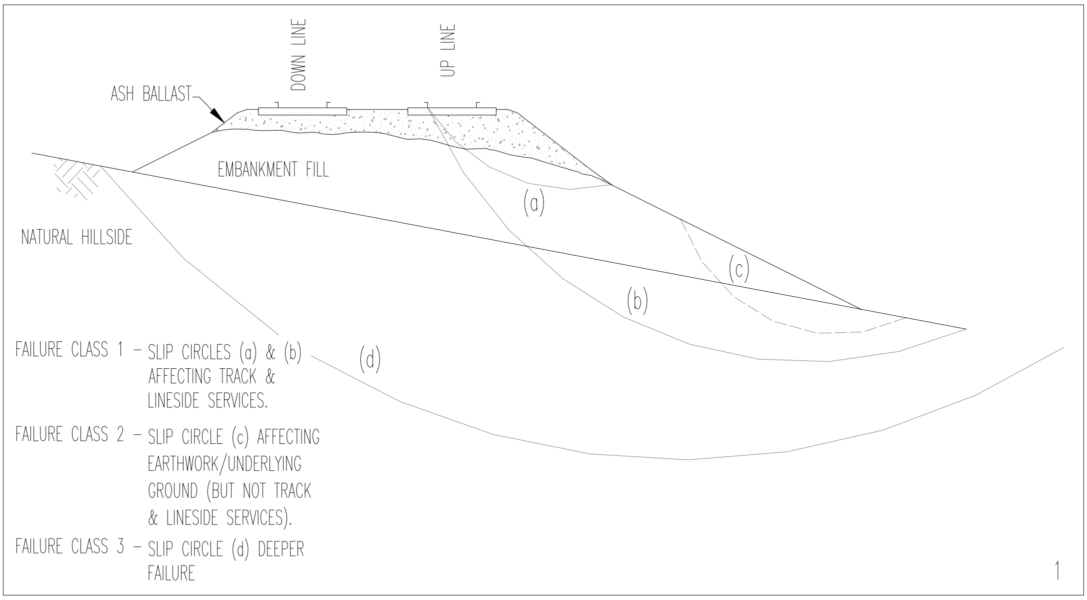

Figure 1 A typical embankment with different classes of potential failure surfaces defined.

In practice an advantage of this approach is that once a remedial works design is complete its adequacy can be summarised on a single sheet print out from a computer slope stability program. This makes the process of scheme review relatively simple, although no detailed knowledge of the actual performance of the earthwork (either pre or post construction) is required.

The use of a Blanket Factor of Safety Approach is certainly useful setting a target for the design of schemes but it is relatively inflexible. It is a ‘blunt’ instrument which it can be argued produces overly robust and conservative schemes. If we are to innovate to improve the cost effectiveness of earthwork remedial schemes the use of the Blanket Factor of Safety Approached must be challenged.

This paper seeks to address the technical arguments for adopting a more responsive design approach (called here the New Approach). For the purposes of brevity and clarity the use of the New Approach is explained for embankments although the approach could equally be adopted for cuttings. In considering the New Approach to earthwork remediation design an understanding of the original construction and how this affects current performance is helpful.

1.1 Typical Railway Embankment Construction and Performance

Most of the earthworks that form the backbone of the UK rail network were constructed in very different times to the present, largely before the advent of mechanised construction plant the work was undertaken by man and horsepower.

Embankments were typically formed by uncontrolled end tipping of 'as dug' material from tipping trucks (Figures 2 & 3). Much of the soil came from adjacent cuttings without consideration of the suitability of its engineering behaviour. The tipped material was simply dumped and allowed to find its natural angle of repose without recourse to any 'engineering' compaction.

Figure 2 End tipping of material during the construction of the 15m high Wolverton embankment on the London to Birmingham Railway circa 1835. Note the tipping truck on the top of the embankment.

Soil mechanics theory (equation 1) tells us that a dry cohsionless soil when tipped will stand in a slope at an angle equal to its internal angle of shearing resistance – in other words with a factor of safety of 1.0.

$$Fos = \frac{Tan\phi'}{Tan\beta} \qquad \text{Eq. 1}$$

Where:-

β = angle of inclination of slope from horizontal

ϕ' = effective angle of shearing resistance of the soil

Most dumped soil would not have been dry but saturated or partly saturated however it would still have come to rest and formed an embankment with a factor of safety of about unity under the prevailing conditions. Where the soil was clay bound it would have been dug in clods and when dumped there would have been voids between the lumps which would have led to immediate and long term deformation and settlement. Preferential paths allowing percolation of water through the structure could also be established with the potential to lead to softening and weakening of the soil through 'deep seated' creep and in extreme cases failure. All these mechanisms lead to loss of track line and level.

In addition other factors such as animal burrowing, scour from adjacent water courses, other external influences can also have a bearing on embankment performance.

Figure 3 A typical tipping truck used in the construction of earthworks. From a wash drawing by John Cooke Bourne, taken from a collection of views of the construction of the London & Birmingham Railway (LBR).

Vegetation, which has been allowed to populate the lineside since the end of the steam era (when trees were cut down to reduce fire risk), can also play a significant part embankment movements. The influence of trees is recorded either while they continue to grow on the earthwork or when they are removed. Andrei (1999) recorded up to 35mm track settlement attributed to seasonal shrinkage induce by mature trees left in place on an embankment side slope following construction of an earthwork buttressing remedial scheme. Egan and Rudrum (2000) noted a 25mm heave at track level on a 10m high embankment a year after remedial works were completed and where dense vegetation and mature trees were removed. These data exclude changes in track level due to re-ballasting or tamping. No direct detrimental impact on the running of trains was recorded in either case even though the values were near or exceeding those specified in RT/CE/S/071. These experiences raise interesting questions of how to select appropriate deformation criteria to measure performance of earthworks 'in service'.

In the early days adding light weight ash/clinker fill and later ballast to maintain track levels was the pragmatic means of accommodating embankment settlement. As embankments settled against 'hard' structures such as bridges differential settlement is often particularly acute and relatively large depths of ash fill is often recorded at these locations.

The placement of ash/clinker or ballast over the original plan width of the embankment while dealing with track geometry leads to the formation of an over-steepened crest shoulder (see Figure 4). Over time the support provided by the ballast and ash reduces due to the process of ravelling whereby soil particles roll down the slope one by one, often under dynamic excitation produced by the vibration of passing trains. In due course this not only leads to loss of track support but loss of a cess walkway as well. Later practice of re-ballasting by placing new material on top of old stone often exacerbates the over-steepening problem.

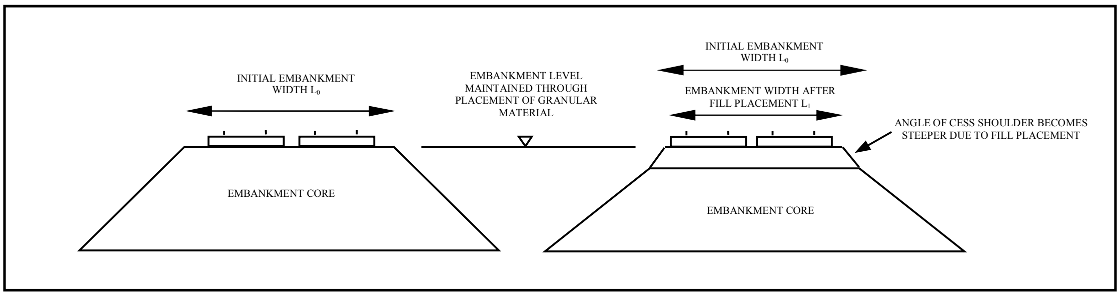

Figure 4 Illustrating the formation of over steep embankment shoulders developing as a result of settling of the embankment core material.

Interestingly 'deep seated' creep or failure is often most prevalent in or after wet periods, while ravelling of ash/clinker and ballast fill is more significant in the dry summer months. Cyclic seasonal effects on earth structure performance must therefore be considered when determining the causes of poor earthwork performance and the effectiveness of remedial measures. Figure 5 shows data acquired over a three year period from an electronic inclinometer installed towards the crest of an embankment near Ilkley in North Yorkshire. The data show a clear cyclic seasonal response within a more general trend of movement.

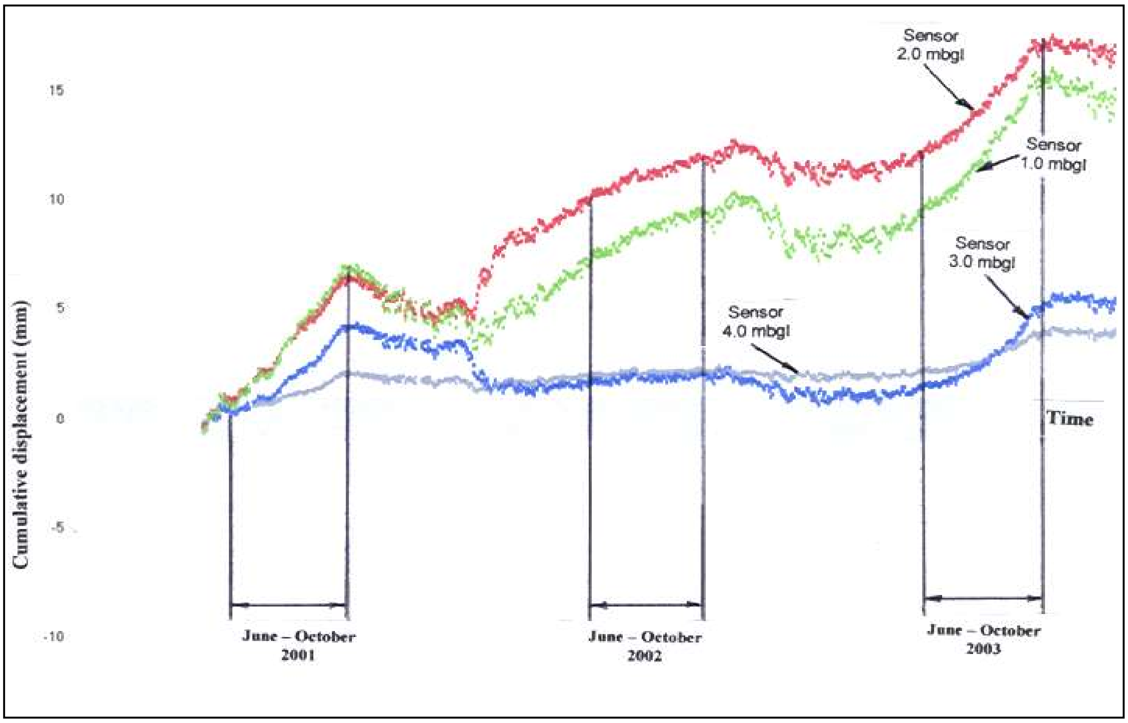

Figure 5 Showing the seasonal effects on cumulative down hill displacement (+ve direction on x-axis) at different depths measured over a three year period by an electronic inclinometer at Ilkley Embankment, North Yorkshire.

To summarise, most earthworks are likely to be deforming in response to a range of mechanisms (as depicted in Figure 6) and given the above analysis it is surprising that most perform as well as they do. In the case of embankments it is presumed that where deformation is occurring at a rate that is naturally accommodated by the general maintenance requirements for the track and ballast over a given section of line earthwork performance is not called into question. In terms of the impact of running trains on the network problem sites are those where embankment deformation is of a magnitude that exceeds that masked by the general regime of track and ballast maintenance. These are the problem sites.

It is from this point that a paradox develops. Poorly performing embankments (or sections of embankment that are performing poorly) are subjected to remedial works which bring the Blanket Factor of Safety up to the prescribed level (typically 1.3). In practice the use of the existing methodology can result in relatively short sections of remediated earthwork with relatively high factors of safety situated between long lengths that would not satisfy the Blanket Factor of Safety requirements but are still judged, by other operational criteria, to be performing satisfactorily. This being the case it should be possible to deal with poorly performing earthworks in a more targeted way by implementing lighter weight and cheaper solutions providing the safety of the network is not put at risk.

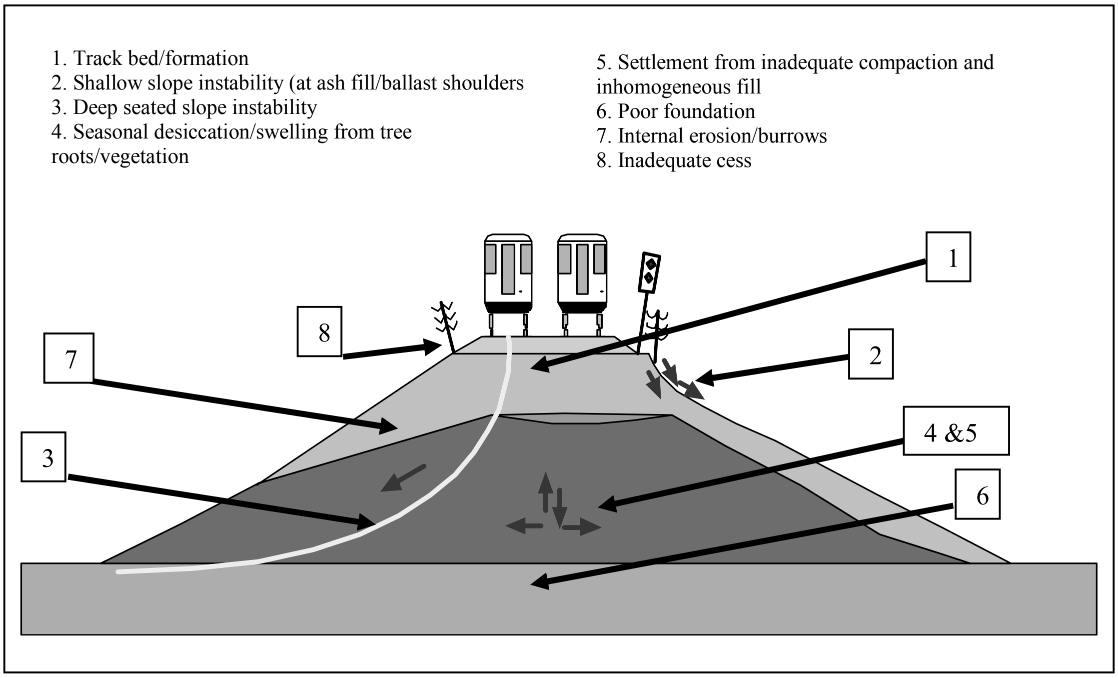

Figure 6 Typical embankment deformation mechanisms.

2.0 CHALLENGING THE PARADIGM

If it is accepted that much of the earthwork asset is deemed to be performing acceptably from an operational point of view but exists with factors of safety (at the Ultimate Limit State) of often much less than 1.3 do all earthworks that are performing unacceptably need to be remediated to the 1.3 blanket factor of safety threshold? In terms of obtaining 'best value' a more liberal approach could be adopted.

2.1 The New Approach

The New Approach to dealing with poorly performing earthworks would comprise of the following stages.

Stage 1:

Undertake a carefully targeted appraisal of the site to define the key deformation mechanisms affecting the earthwork. This can be a very difficult task due to the constraints of working in the rail environment often with poor (or absent) access. At this stage, if done over sufficient time and with sufficient care, it should be possible to separate out the magnitude and effect of various deformation mechanisms (shallow shoulder ravelling, deep seated instability, seasonal shrink swell, settlement from inadequate compaction of inhomogeneous fill, poor foundation, animal burrows etc) to allow the key mechanisms to be identified. In other words seek to answer the question What 20% of sources are causing 80% of the problems?

It is important that this stage in the asset management process is not compromised if the overall target is to construct lighter weight targeted remedial works. Conversely inadequate attention to this phase of the process both in terms of time and resources made available and the targeting of investigation and monitoring will impact the rest of the project. The old army maxim 'time spent in reconnaissance is rarely wasted' is appropriate;

Stage 2

Develop remedial works to address the key mechanisms that are affecting track performance, but do not necessarily seek to remediate the whole earthwork to a predefined 'Blanket' Factor of Safety. Targeted remedial works can be implemented to address the key mechanisms of poor performance. Indeed for common problems the adoption or development of 'standard' solutions could be facilitated (For example the Ruglei system). In developing remedial solutions a selective approach could be taken. For example if the problem is one of shallow crest instability (shoulder ravelling) the solution may be to just address this without significantly improving factors of safety for deeper failure mechanisms – providing of course the no part of the blanket stability of the earthwork is detrimentally reduced. Taking a targeted approach, based on a rational methodology would reduce the practice of having to produce overly conservative remedial schemes so that all factors of safety exceed the specification requirements.

3.0 EXAMPLE OF USE OF THE NEW APPROACH

3.1 Ilkley Embankment

The principles behind the development of an embankment remedial scheme on the Leeds-Ilkley line illustrate how a more flexible approach can be adopted. Network Rail London North Eastern Territory procured this scheme on a Design and Build basis through the May Gurney Structures Framework agreement, with Atkins Rail acting as the designer.

The site comprises a 750m long stretch of embankment on side long ground (ILK02, 209.0374 yards to 209.1188 yards). The nature of the earthworks is dictated by the variation in hillside topography. On the downhill side the embankment ranges from 2m to 14m in height. On the uphill side the line alternates from being on an embankment up to 6m high to being in cutting up to 6m deep across the site. The line was constructed in the 1860's across a prehistoric landslip located on the north facing side of the Wharfe valley. Parts of the wider hillside area are still subject to active instability. The geology and morphology of the area is complex and artesian ground water pressures were identified as a significant driver of hillside instability.

The embankment exhibited a number of deformation mechanisms (as shown in Figure 7) including:-

i. Shallow and deeper seated instability/deformation affecting the underlying hillside on which the embankment is built (Failure Class 3);
ii. Creep deformation affecting the near surface hillside material and embankment toe (Failure Class 2);
iii. Ravelling of the over steep granular material at the embankment crest (Failure Class 1).

The initial design for the remedial works was undertaken to achieve a Blanket Factor of Safety of 1.3 for failures affecting the embankment based on moderately conservative peak parameters. (Achieving a calculated factor of safety of 1.1 using residual parameters in locations where defined failures could be identified was also permissible.)

Figure 8 shows in outline the Blanket Factor of Safety remedial solution.

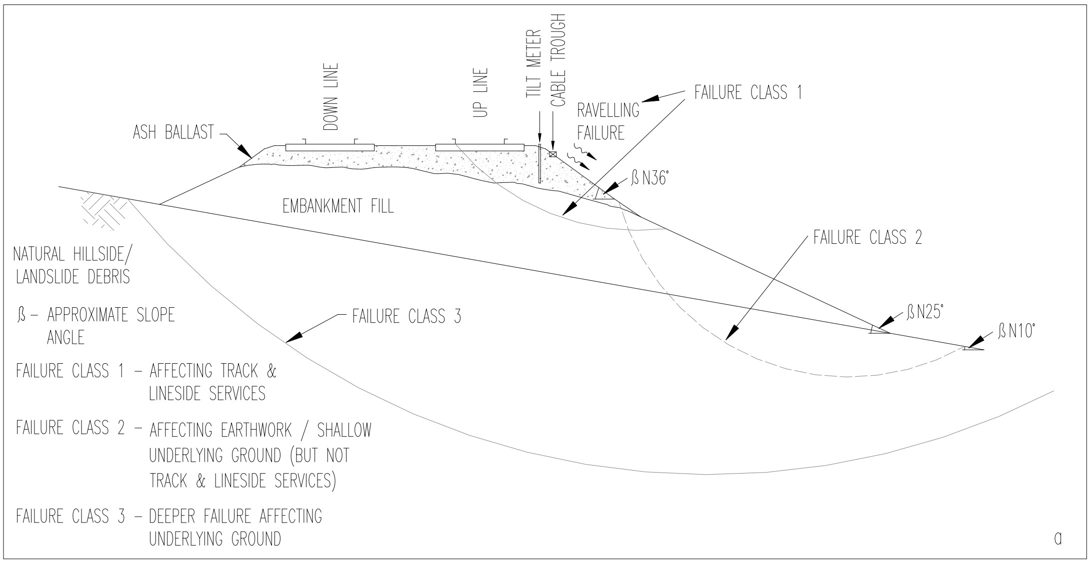

Figure 7 Failure types affecting Ilkley Embankment

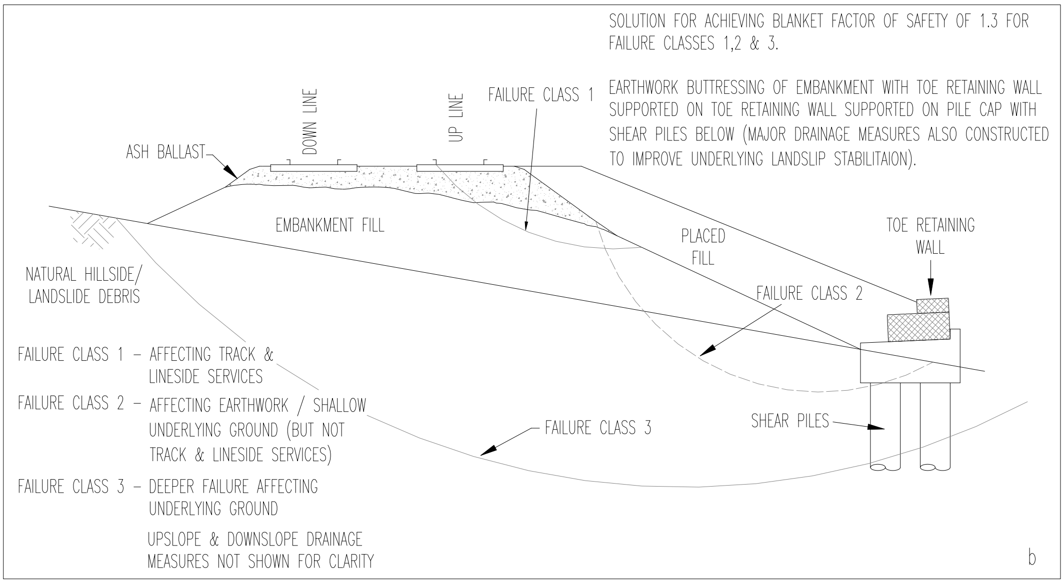

Figure 8 Indicative remedial works to achieve a Blanket Factor of Safety of 1.3 for potential failures affecting the embankment

It was clear from an early stage that following the Blanket Factor of Safety approach would result in a very robust (and expensive) scheme. Therefore Network Rail agreed that a value engineering exercise be carried out quantify the cost impact on the basis that lower factors of safety could be accepted. The project was considered in two phases. Phase 1 included the implementation of drainage measures mainly to address the causes of the underlying hillside instability. The value engineering exercise led to some savings in this phase of work. Phase 2 would comprise embankment buttressing works that would address key mechanisms affecting track geometry in a carefully targeted way. Table 2 shows the factors of safety proposed for the value engineering exercise.

The option for utilising more targeted lighter weight measures to address key mechanisms (such as cess ravelling) is realistic and Figure 9 shows how this might be achieved at this site.

Failure Class	**Target Design Factor of Safety (Moderately conservative peak soil parameters)**	**Target Design Factor of Safety (Moderately conservative residual soil parameters)**

Failure Class 1 – affecting track & lineside services.	1.3	1.1
Failure Class 2 – affecting the earthwork & shallow hillside deposits (not directly affecting the track or lineside services).	1.2	1.1
Failure Class 3 – Deeper failures.	Not less than calculated for the pre-works condition.	1.1

Table 2 Design Factors of Safety for Ilkley remedial works following the value engineering exercise.

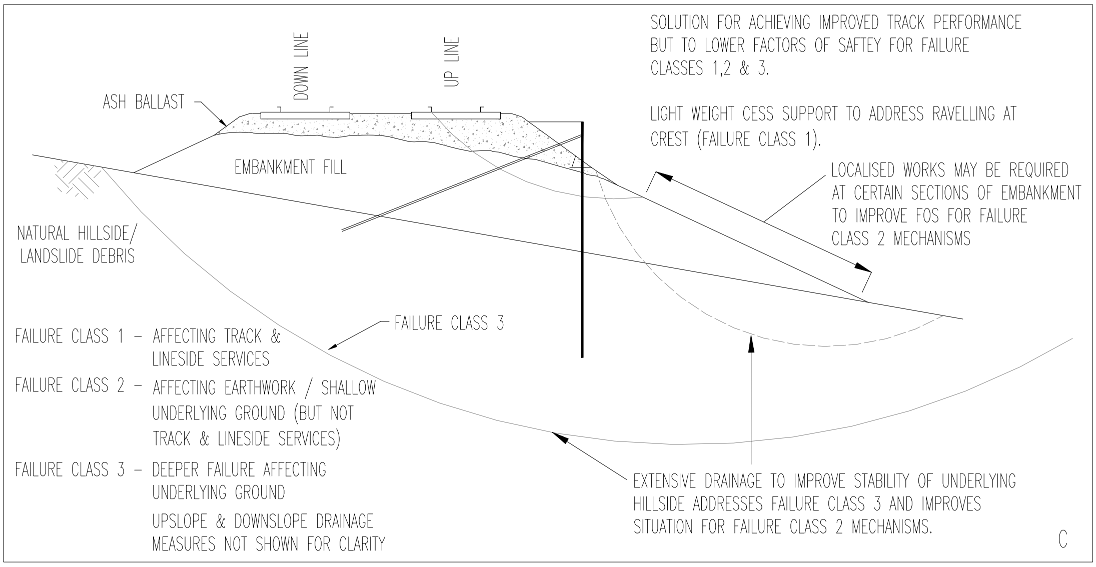

Figure 9 Possible lighter weight remedial works to target primary deformation mechanisms at Ilkley.

3.2 Conclusions from the Ilkley Experience

The above illustration from the development of remedial works for Ilkey Embankment shows how a flexible approach to the design of such schemes can produce significant savings. Most problem earthworks schemes do not fall within areas of the same level of geological complexity as the Ilkley embankment, however there is no reason that the philosophy used here can not be used on other earthwork schemes.

4.0 SUMMARY

The widely used and currently accepted philosophy of designing earthwork remedial measures is based around the design achieving a predefined Blanket Factor of Safety irrespective of the key mechanisms of deformation that are having the most significant impact on the running of trains. A New Approach has been proposed where greater emphasis is placed on producing lighter weight and cheaper solutions that target the source of key mechanisms that are affecting track performance. Essential to this approach is the initial data gathering and appraisal stage where adequate effort has to be expended, in a controlled manner, to identify the key drivers of instability. Once identified, these can be addressed by lighter weight targeted remedial works.

5.0 CONCLUSION

The aim of this paper is to challenge the current way we think about the design of earthwork remedial schemes. In some small way the opinions set out in this paper resonate with the thoughts of Ralph Peck (friend and colleague of Karl Terzaghi) outlined in a paper entitled ‘Pitfalls of Overconservatism in Geotechnical Engineering’ (Peck, 1977), in which he challenged the concept that *‘if a little conservatism is good, more must be better’*. Peck concluded his paper by saying…

"All of these steps are possible to a large extent now. They will require perseverance, hard work, and clear judgement. Those who persist may even run the risk of criticism or liability, but they will have advanced the welfare of the public and the stature of the profession of engineering."

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