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A whole life cost model for earthworks slopes

Prepared for Quality Services, Civil Engineering Division, Highways Agency

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Scope of the project

The Highways Agency is becoming increasingly interested in the whole life costs of designing, constructing and maintaining the side slopes of highway earthworks. Previous outputs in the research programme (LOA E060A/ HG Ground Properties) have identified failure mechanisms for highway slopes and a database has been assembled for a wide range of slopes and materials. A risk based approach would enable a balance to be achieved between selection of the initial slope angle and the likely incidence of future slope failures. The research aims to develop a whole life cost approach to earthworks. The research is particularly relevant to Design and Build as slope failures continue beyond the handover period. The research is relevant to Eurocode 7 (Geotechnics) and the development of a National Application Document (NAD).

The project commenced in September 1995 and was completed in March 1998. This report and the accompanying computer programme WLCslope version 1.0 and User's Manual are the final outputs from this project.

Summary

The problem of minor slope instabilities on the motorway and trunk road network has been described by Symons (1970) and Perry (1989). The problems are mainly confined to overconsolidated clays and to particularly high sections of embankments or cuttings, but the ongoing cost of repairs to the slope failures constitutes a significant amount of maintenance expenditure.

The problem of balancing construction and maintenance expenditure on earthworks slopes was addressed by the development of a whole life cost model and computer programme. The resulting programme, WLCslope, enables comparisons to be made between different design options on a whole life cost basis rather than solely on the basis of capital cost. It also allows comparison of the residual maintenance costs for different options for DBFO contracts, where the responsibility for maintenance reverts to the government after 30 years.

Application of the model to a range of soil types indicates that the maintenance component of the whole life cost may be up to 3.7 times the capital cost for soils with a high rate of slope failure. In some cases, the whole life cost for a 1:5 slope may be significantly lower than that for a 1:2 slope because of the slope repair costs associated with the steeper slope. Residual costs may be in the range 5% to 10% of the whole life cost at 30 years for steep slopes with high failure rates. Variations in land price and discount rate have a major impact on the results of the analysis.

Implementation

The programme may be used as a means of assessing different options for earthworks slope design on new construction on a whole life cost basis. It may also be used to compare the residual maintenance costs after 30 years for different options on DBFO contracts. The programme produces graphs of Net Present Cost (NPC) against time and tabulates values of the capital cost, NPC at 30 years (NPC_{30}) and NPC at 60 years (NPC_{60}) for each earthwork. The user must specify the earthwork type, slope angle, length, height, soil type, failure rate, number of years for which the analysis is to be carried out, discount rate, land price, construction costs and repair costs. Default values are provided for discount rate, land price, construction costs, repair costs and failure rates for a range of soils.

The model should not be used to estimate actual costs for construction or maintenance; it is designed to allow comparison between options on a whole life cost basis. The model is capable of further development and would benefit from further research into the rate of minor slope instabilities for a greater variety of soil types. More information on long term failure rates would be particularly valuable, as the data on which the model is based only extend up to 30 years from construction.

References:

Perry J (1989). *A survey of slope condition on motorway earthworks in England and Wales*. Research Report RR199. Transport Research Laboratory, Crowthorne.

Symons I F (1970). *The magnitude and cost of minor instability in the side slopes of earthworks on major roads*. Laboratory Report LR331. Transport Research Laboratory, Crowthorne.

1 Introduction

The design of earthworks slopes for highways has developed with the growth of the motorway system since the late 1950s. Before this, most roads followed the ground surface fairly closely; there were few earthworks of any height, and consequently few failures. With the introduction of stricter limitations on horizontal and vertical alignments for motorways, much larger earthworks became necessary. This in turn led to improvements in site investigation, laboratory testing and slope stability analysis as design methods were developed to cope with the increased scale of the earthworks. The concepts of effective stress and pore pressures, already employed in the design of embankment dams, were applied to highway earthworks, as exemplified in BS 6031 Code of practice for earthworks (British Standards Institution, 1981). These methods have proved extremely effective in preventing major, deep seated instabilities on motorways and major trunk road improvements to date.

Although major instabilities are rare, minor shallow instabilities have occurred on cutting and embankment slopes in certain materials from the start of the motorway era. Data on the subject are summarised by Symons (1970), who examined records of repairs for 350 km of motorway and 140 km of major trunk road. He found that instability was mainly confined to short lengths of relatively deep cutting and high embankment, that it occurred mainly in overconsolidated clays and was often linked to local drainage conditions which channelled water onto the slope. The failures accounted for less than 7 per cent of the motorways surveyed and a negligible proportion of the trunk roads.

As the motorway network expanded in the 1970s and 80s, so did the problem of minor slope instabilities. Much effort was dedicated to understanding why the failures occurred and how they could be repaired (eg. Crabb and West (1985); Crabb and Atkinson (1991); Greenwood, Holt and Herrick (1985); Johnson (1985); Murray, Wrightman and Burt (1982); Parsons and Perry (1985); Perry (1985); Perry (1991)). Failures were most frequent in overconsolidated clays and were linked to softening of the outer part of the slope by rainfall or runoff. Slopes were generally designed on the basis of peak shear strength parameters derived from laboratory tests, sometimes with an adjustment to the effective cohesion or pore pressures to reflect anticipated long term conditions. As a result of observations of minor slope failures the mechanisms of failure became clearer, and it became apparent that in overconsolidated clays the outer face of the slope reduced to the critical state strength at the time of failure. At this stage some of the material was at residual strength near the toe of the slip, where movement had already started. Most of the material on the slip surface was between residual and peak strength, and only a small section was still at peak strength. The critical state strength represents an approximation to the average value of shear strength along the length of the slip surface. However, design of slopes continued to be based largely on peak strength parameters, generally with the aim of maximising the slope angle and minimising the land take. This inevitably meant that many slopes in overconsolidated clays were constructed at slope angles that would lead to minor instabilities in the future.

The extent of these minor instabilities was revealed by a detailed survey of 570 km of the motorway system in England and Wales carried out by the Transport Research Laboratory (TRL) in the 1980s (Perry, 1989). The survey covered over 20% of the motorway network and included a wide range of the most common soil types encountered. Over 17 km of embankment slope and over 5.5 km of cutting slope was found to have failed. This represents about 4% of the total length surveyed. The depth to the failure surface rarely exceeded 1.5 m below the slope surface. The geologies with a high percentage of failure were dominantly high plasticity overconsolidated clays, in particular the Gault Clay, Reading Beds, Kimmeridge Clay, Oxford Clay and London Clay. It was estimated that three times as many slopes were likely to fail than had failed so far if no preventative measures were taken. Based on the wide range of slope angles and heights observed, maximum recommended slope angles for less than 1 per cent failure within 25 years of construction were given for a range of geologies in cutting and embankment. In contrast to the theoretical approach to slope design discussed above, the recommendations of Perry (1989) were based purely on empirical observations of existing slopes. The recommended slope angles were generally much flatter than those commonly employed on highway earthworks, and would have implications for increased land take and construction costs.

Failures on the slopes of highway earthworks are undesirable. They can undermine the road structure, damage drainage, cabling and safety fences, and in some cases obstruct the motorway hard shoulder. Furthermore, reinstatement of failed slopes results in higher maintenance expenditure. This has to be balanced against the higher land take and construction costs associated with constructing slopes at flatter angles which would not lead to future minor instabilities. The method of whole life costing, already widely applied to road pavement and bridges design, offers an opportunity to balance these costs over the design life of the earthworks.

The introduction of Design, Build, Finance and Operate (DBFO) contracts in recent years has given further impetus to the whole life costing of highway earthworks. Under the terms of the contract, the DBFO consortium are responsible for building a section of highway and maintaining it for a period of usually 30 years, after which it is handed back to the Highways Agency (HA). It is important for HA to be able to predict the likely expenditure on remedial earthworks when the road is handed back, and to include these future liabilities when assessing DBFO tenders from different contractors. A whole life cost model for earthworks would enable these factors to be assessed on a logical and quantitative basis. The HA has recognised that there is a direct relation between the way a scheme is designed and constructed and its whole life operational costs (Highways Agency, 1997).

As a result of the above considerations, HA commissioned TRL in 1995 to carry out a research project into producing a whole life cost model for earthworks slopes. The objectives of the research were:

1 to develop a whole life cost approach to earthworks design and construction;
2 to allow the Agency to develop a balance between initial construction cost and maintenance spending;
3 to award tenders on the basis of whole life costs, which will be of particular importance for Design and Build and Design Build Finance and Operate contracts;
4 to develop a computer model to calculate whole life costs for highway earthworks.

This project report and the accompanying computer program and user's manual are the result of the research. The technical background to slope failures and repairs in highway earthworks and whole life costing is discussed in chapters 2 and 3. The background assumptions and methods of calculation of the model, and the development of the computer program are described in chapters 4 and 5. The program was written in Visual Basic with the aim of being as user-friendly and flexible as possible. A number of tests were run with the model to assess the effect of changes in the various input parameters; the results of this work are presented and discussed in chapter 6. Suggestions for further work are given in chapter 7 and the conclusions are summarised in chapter 8. Further relevant technical details and an example calculation are given in the appendices.

Before concluding this introduction, it is worth noting that the concept of whole life costing for highway earthworks is not new, although the terminology may be; the last paragraph of the report by Symons (1970) reads as follows:

> *'As a next step, therefore, a cost benefit study will be carried out to examine the overall economics of slope design. In this work consideration will be given to both the construction and maintenance costs for a wide range of slopes from the steepest at present in use to ones sufficiently flat to enable the slopes to be returned to the riparian owner.'*

Thirty years later, this study has finally been carried out.

2 Slope failures and repairs in highway earthworks

2.1 Failures

2.1.1 Extent and type of failure

The survey reported by Perry (1989) showed that shallow failures are a significant maintenance problem on motorway earthworks. Most failures occurred in overconsolidated clays whether in embankments or cuttings. For steep and high earthworks in these materials almost all slopes had failed. Within the first twenty five years of construction, the type of failure observed varied from distinct slab type to shallow circular type but with most slips having a combination of translational and circular movement. When comparing embankments with cuttings, the geometry of the slips was very similar.

The six individual geological units in which slopes were found to have the highest percentages of failure in embankments and cuttings are shown in Table 1. For embankments, the table includes most of the well-known overconsolidated clays. Most of the failures in the Lower Keuper Sandstone were of the topsoil and not of the fill itself. In cuttings, well-known overconsolidated clays are again included as well as the Enville Beds. London Clay, a well-documented material because of its unstable behaviour, was not one of the six worst geological formations in cuttings. This may be due to the flatter slope angles generally employed for this material because of its behaviour; in the survey, the predominant slope angle for London Clay in cuttings was 1:3, compared with 1:2 for the same material in embankments.

Table 1 Geological formations with a high percentage of failure (from Perry, 1989)

Geology	*Percentage of failure*	*Predominant slope angle*
Embankments		
Gault Clay	8.2	1:2.5
Reading Beds	7.6	1:2
Kimmeridge Clay	6.1	1:2
Oxford Clay	5.7	1:2
Lower Keuper Sandstone	4.9	1:1.5
London Clay	4.4	1:2
Cuttings		
Gault Clay	9.6	1:2.5
Enville Beds	5.8	1:2.5
Oxford Clay	3.2	1:2
Reading Beds	2.9	1:3
Bunter Pebble Beds	2.3	1:2
Lower Old Red Sandstone - St Maughan's Group	1.7	1:2

In some cases, a combination of geological units was found to have a higher percentage of failure than the individual units. Examples include Glacial Gravel with Middle Lias in embankments, which had a failure rate of 11.0 per cent, and Middle Lias over Lower Lias in cuttings, for which a failure rate of 13.1 per cent was recorded, the highest in the survey. Overconsolidated clays are involved in both cases.

The study of the effect of geometry on slope stability unexpectedly revealed that the steepest slope angle on overconsolidated clays is not necessarily associated with the highest percentage of failure. Cutting and embankment slopes in overconsolidated clays have a high initial strength due to the negative pore water pressures resulting from stress relief during construction (Skempton (1977); Crabb, West and O'Reilly (1987)). Slope angle is one of the parameters which influences the rate at which this pressure changes, with the most rapid reductions occurring on flatter slopes which do not shed water readily (Vaughan and Walbanke (1973); Chandler and Skempton (1974); Chandler (1984)). On the other hand, disturbing forces are greatest on the steepest slopes and failures result from an interaction between these and the greater shear strength due to lower pore water pressures. Crabb and Atkinson (1991) and Perry (1991) have shown that shallow failures are long term drained failures. The mechanism is a combination of two effects. The first is the swelling and softening of the near surface material which, under the influence of shear strains in the slope, reduces its strength towards the critical state. The second is the equilibration of rainwater into the slope surface with flow through the slope, and evapotranspiration and shedding of water at the surface.

Perry (1991) and Crabb and Atkinson (1991) showed that the critical state (or fully softened) strength should be used to assess shallow slope instability of overconsolidated clays. They carried out back analysis of a number of slope failures and found consistent results. The critical state strength provides an approximation for the strength mobilised over a failure surface. The progressive nature of shallow slope failures results in parts of the failure surface exhibiting small strains which mobilise peak strength while larger strains elsewhere mobilise residual strength, having passed beyond the peak strength. The critical state strength is therefore not the ‘real’ strength parameter in this application but provides a very good basis for design.

Overconsolidated clays when excavated, transported and placed in embankments exhibit greater suctions than was previously recognised; as in cuttings, the increase in pore water pressures with time from these highly negative values to equilibrium or slightly positive values leads to failure. Field observations by Perry during the motorway slope condition survey and theoretical work by the Geotechnical Consulting Group (1993) showed that failure starts at the base of the slope and progresses to the slope crest. The pore water measurements of Atkinson and Farrar (1985) and Crabb, West and O’Reilly (1987) showed that the plane of pore water pressure equilibrium is at about one to two metres depth, that is at the depth of failure, and that higher pore water pressures can develop only at the toe.

The outer layer of an earthwork in a clay soil is prone to shrinkage cracking and seasonal water infiltration. The measurements of pore water pressure undertaken by TRL (Crabb and Hiller (1993); Crabb (1994)) show that the pore water pressure changes both with time and depth into the slope. The outer one to two metres are very susceptible to rises and falls in pore water pressure. The speed and extent of change is facilitated by the shrinkage cracking. Below this zone of cracking, pore water pressures change very little and the permeability of the material is very low.

From the above observations, it is clear that the outer zone of an earthwork is particularly vulnerable to failure as a result of increased positive pore water pressures. This agrees with the survey observations that slope failures are dominantly limited to the outer 1.5 metres of the embankment and cutting slopes.

2.1.2 Rate of slope failure

The survey by Perry (1989) recorded the extent of failure at the time of the survey and reached some general conclusions about how the extent of failure varied with the age of the earthwork and what the likely future extent of slope failure would be. This aspect was investigated in more detail by Andrews (1990), who used aerial survey photographs to determine the rate of development of slope failures in cuttings and embankments. The overall failure rates of embankments were often found to be erratic with intervals during which few, if any slips occurred. One clear effect was discovered, namely that cuttings begin to fail at an increased rate several years after construction. The transition to an increased failure rate can be either sudden or prolonged. For both cuttings and embankments there was a strong dependence on the height of the earthworks, with higher earthworks generally failing at a higher rate. The effect of slope angle was more difficult to determine because sample sizes were small, and no clear picture emerged.

The rates of failure recorded by Andrews (1990) showed considerable variation between different soil types. Data were obtained from aerial photographs and ground surveys at intervals of several years, and the results were presented as graphs of cumulative percentage failed against time. As the points were often widely spaced, there was some uncertainty about the exact shape of the curves. There was considerable variation in the shape of the curves; some showed rates of failure increasing with time, some decreasing with time, some were step-like while others showed an apparent uniform rate of failure. Cuttings, in particular, often showed an increase in failure rate after an initial period of low failure rate, with the transition occurring up to 20 years after construction. The rate of failure almost always increased with increasing height of the slopes. Failure rates ranged from less than 0.1% per annum to a maximum of 8.3% per annum. The age range of the surveys varied from 10 years to 25 years.

The lack of comprehensive data makes interpretation of the rate of failure difficult. However, during the present study a complete set of data was obtained for embankments on the A14 Cambridge Northern Bypass from its opening in 1979 to 1996; this is plotted as cumulative percentage failed against time and as the percentage failed in each year in Figure 1. After a very low failure rate for 3 years there was a rapid increase from 3 to 6 years, since when the failure rate has been roughly constant at 0.75% per annum. After 17 years, a total of 15.6% of the total of 19 km of embankments was estimated to have failed. The last survey included in these results, in October 1995, recorded several areas of tension cracks at the top of the embankments. Following the practice of Perry (1989), slopes where cracking has occurred have not been counted as slope failures. However, the presence of the cracks indicates that further failures will occur in the future; measurements by Crabb and Hiller (1993) indicate that more than a year may elapse between the first signs of cracking and the appearance of a distinct back scarp, which is taken as the onset of failure.

The existence of a complete data set for any one section of earthwork is unusual and is due to the particular problems of slope stability which have affected this section of road since construction. The Cambridge Northern Bypass is dominantly on embankment, up to 7 metres in height and constructed at a slope angle of 1:2. The total length of 19 km of embankments includes both sides of the carriageway and several grade separated interchanges and approach roads. Most of these embankments are between 5

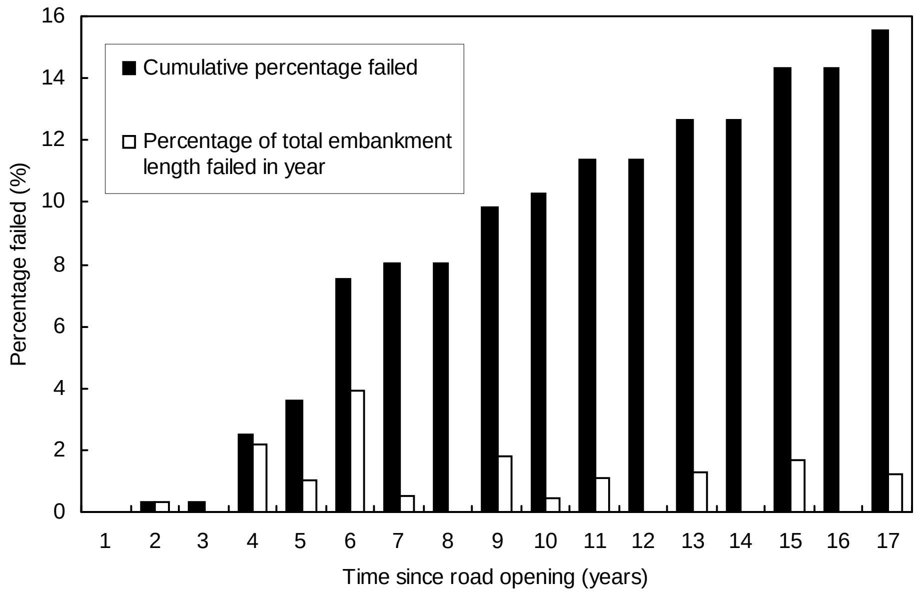


Figure 1 Age distribution of failures on Cambridge Northern Bypass

metres and 7 metres in height. The material used for the embankments was Gault Clay excavated from a local pit adjacent to the road; this material is particularly susceptible to minor instabilities (Perry 1989), especially at such a steep slope angle and at such height. Comprehensive records of slope failures were therefore kept by the Maintaining Agents from the outset, using Form A of HA 48, Maintenance of highway earthworks and drainage (DMRB 4.1.3). Such a complete set of records is very rare and extremely valuable, but it does represent a 'worst case' scenario.

Information on the rate of failure can also be obtained by looking at the age of earthworks when slope repairs are carried out. A database of information on highway slope failures and repairs was produced as part of the project. This is described in more detail in section 2.2.1. The database was examined to investigate the distribution of the ages of the failures in the sample. The age is defined as the time in years between the date of the failure and the opening date of the section of road. The distribution of failures with time since construction is shown on Figure 2. This shows a low number of failures in the first 3 years, rising to a broad peak between 5 and 15 years with a gradual but irregular decline to the oldest recorded failures at 29 years.

An upper limit to the age of failures is given by the age of the roads themselves. Of the examples in the database, over 90% of the failures were on roads less than 25 years old on 30 September 1996. Only a few examples from the M1 in Bedfordshire were on roads more than 30 years old. The database is thus only representative of roads constructed over the last 25 years or so, and contains only limited information on failures on older roads. However, we understand from Midland Network Management Division that no slope failures have been reported on the M1 in recent years, although a number of failures were recorded in the same area in earlier surveys by Symons (1970) and Perry (1989). This is consistent with the general pattern shown on Figure 2, of a large number of failures up to about 15 years after opening of the section of road, then decreasing to a much lower rate of failure in the longer term. Not all slope failures are included in the database, which is based on repairs to slope failures; minor failures which do not threaten the carriageway or surrounding property may not be repaired, and hence would not be included in the database.

The repair database is different in nature from the slope condition survey carried out by Perry (1989). It consists of records of individual repairs at a variety of sites carried out between 1985 and 1996, and is not a comprehensive record of any particular section of road. Data from trunk roads such as the A14 are included as well as data from motorways, whereas the survey by Perry (1989) was restricted to motorways. Nevertheless, many of the conclusions from the two surveys are similar. The repairs were almost entirely restricted to overconsolidated clays, and predominantly to slopes over 3.5 metres in height. The database was dominated by slopes at an angle of 1:2; 60 per cent of the repairs were on slopes at this angle, with only 12 per cent on slopes steeper than 1:2 and 13 per cent on slopes at 1:3 or less.

The age distribution shown on Figure 2 is thus probably broadly representative of the general trend in overconsolidated clays in highway earthworks in the United Kingdom. The data represent a number of soil types, a wide range of heights and both cuttings and embankments. This broad distribution is considered to be typical of the shape of the age/percentage failure curve for most soil types, though the position and height of the peak and the shape of the curve will vary between different soil types and, probably, between the same soil in different locations. However, further research into the actual rates of slope failure for particular soil types would be extremely useful.

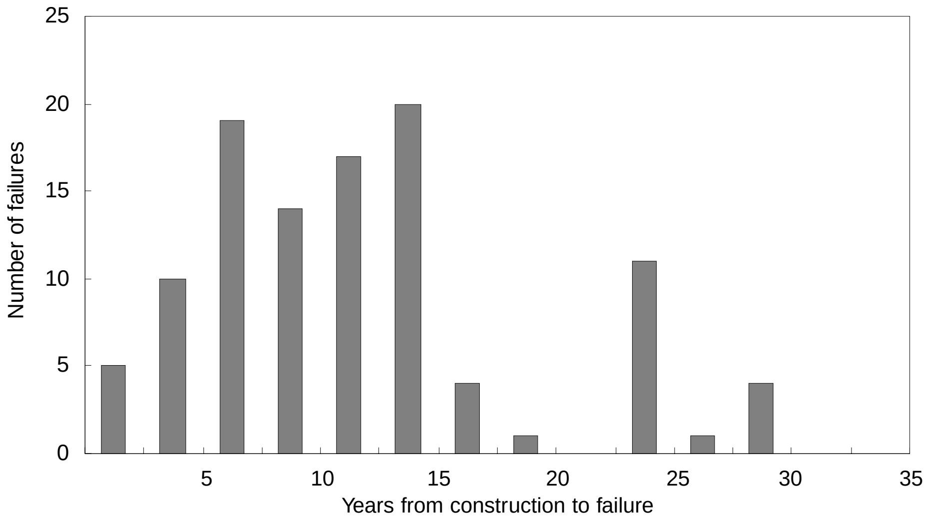


Figure 2 Distribution of failures with time since construction

2.2 Repairs

2.2.1 Slope repair database

As part of the present project, a search was made for information on highway slope failures and repairs. Initially most information was obtained from the Highways Agency Midland Network Management Division, Bedford and Technical Services Division, Bristol. The data were based mainly on Forms A and B of HA 48, Maintenance of Highway Earthworks and Drainage (DMRB 4.1.3), together with relevant correspondence and reports. Further information was subsequently obtained from a number of Maintaining Agents, generally County Councils.

In order to calculate the Net Present Cost (NPC) for each section of highway, it is also necessary to know the construction date and cost. This information was obtained from Government publications (Department of Transport, 1968, 1975, 1976, 1978, 1980, 1981, 1983, 1985, 1986, 1987, 1996).

The information was reviewed and a database created to record the data for individual slope failures. The number of cases which were included in the database was much smaller than the number of failures recorded, because in many cases essential details were missing, such as the date of the repairs or the cost. Only those cases for which reliable data were available were included in the database; 106 cases in total have been included.

The initial data was from only four counties, Essex, Bedford, Cambridge and Hertfordshire. The failures were dominantly in embankments in overconsolidated clays. Further data were obtained from Kent, Gloucester, Lincolnshire, Warwickshire, Staffordshire and Cumbria, but the preponderance of embankments of overconsolidated clays was maintained. Out of the 106 data points, 82 (77%) were for embankments and 24 (23%) for cuttings. The materials in which failures occurred were mainly the Gault Clay, London Clay, Oxford Clay and Lias Clay, with smaller numbers of failures in Glacial Till, weathered Mercia Mudstone, Woolwich and Reading Beds and Weald Clay. Failures in granular material were very rare, and where they did occur were invariably associated with underlying cohesive materials in the cutting or embankment slope face.

The height distribution of the slopes which have been repaired is shown on Figure 3. The bulk of the repairs are in slopes of over 4.0 m total height. The greatest numbers are in slopes between 5.5 m and 7.5 m in height, with smaller numbers in slopes of up to 14.0 m in height. Most of the slopes greater than 10.0 m high are in cuttings rather than embankments, though overall embankments outnumber cuttings by 3 to 1. The lowest slope in which a repair was carried out was 2.5 m.

The length of a repair is not necessarily the same as the length of the failure. Individual failures are seldom more than 30 m to 50 m in length. However, frequently a number of slips occur adjacent to one another and a repair is carried out over the whole length affected, which may be up to 300 m. (It should be noted that the percentage of length failed calculated for the A14 in the previous section and the figures quoted from Perry (1989) and Andrews (1990) are for actual lengths of failure, not overall lengths of repair.) As a result, repair length does not show a good correlation with repair height.

2.2.2 Types of repair

Both Symons (1970) and Perry (1989) recorded that repairs to slope failures almost without exception consisted of excavation of the failed material and replacement with granular free-draining material such as gravel, brick rubble or crushed rock. ‘Granular replacement’ relies on the availability of free draining material and has the advantage of requiring very little supervision. However, in areas where granular materials are scarce and expensive, the trend in recent years has been to adopt reinforced soil slope repairs. This involves layering soils between geotextile sheets and allows reuse of the failed material. Although very economic in materials it does require good supervision and careful construction. These and other less commonly used methods of repair are described in HA 48 Maintenance of Highway Earthworks and Drainage (DMRB 4.1.3).

In the cases recorded in the slope repair database, the repair methods consist mainly of geogrid reinforcement

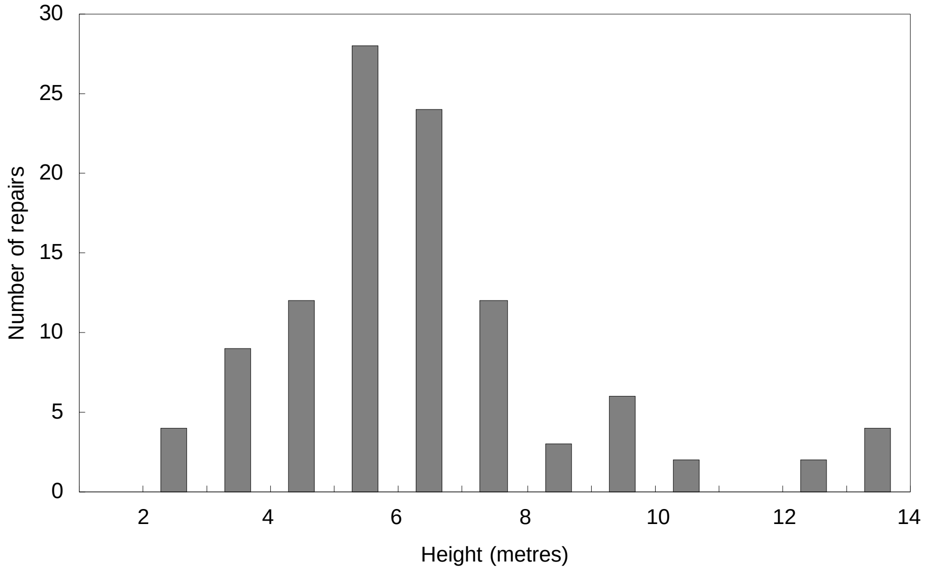


Figure 3 Height distribution of repairs

with reuse of the failed material, treated with lime if necessary to dry it out. There were a smaller number of cases of granular replacement. The number of geogrid reinforcement repairs was 76 (72%) and the number of granular replacement repairs was 30 (28%). Geogrid reinforcement was dominant in the south and east of England, where granular materials are scarce, and granular replacement was dominant in the north and west, where these materials are more readily available. The heavily overconsolidated clays which are most susceptible to slope instability are most common in the south and east, hence there is a greater number of data points for this area and a greater number of geogrid reinforcement repairs.

Except in cases where the carriageway is threatened, there is a delay of months or years between the reporting of a failure and its repair. Most repairs are carried out within 4 years of being reported, and the pattern has not changed over the period covered by the survey (1984 - 1996). The average delay is about 2 years; exceptionally, delays of up to 12 years are reported.

2.2.3 Costs of individual slope repairs

The costs of individual slope repairs can be assessed from the slope repair database. The cost of a repair was found to be closely linked to the length of the section. This applied to all data (Figure 4(a)), without any correction for the date of the repair. This suggests that repair costs have not altered significantly over the period covered by the sample (1985 - 1996). When the data were broken down into the two main methods of repair, geogrid reinforcement and granular replacement, the correlations were found to be not significantly different. Regression equations for each case and the combined data were calculated and are summarised in Table 2. The correlation coefficients were significant at >99.9% level in all cases. Overall, the average cost of a repair was £633 per metre length.

The costs were adjusted to November 1995 prices using the local authority highway maintenance and lighting price index. The results are plotted on Figure 4(b). The

Table 2 Correlation between repair cost and length

Parameter	*Granular replace -ment*	*Geogrid reinforce -ment*	*Combined data (unadjusted costs)*	*Combined data (1995 prices)*
Number of cases	30	76	106	106
R Squared	0.933	0.806	0.829	0.826
Constant	-3.046	1.467	0.433	-1.058
Coefficient	0.705	0.591	0.620	0.823
Std Err of Y Est	8.027	15.585	14.384	19.267

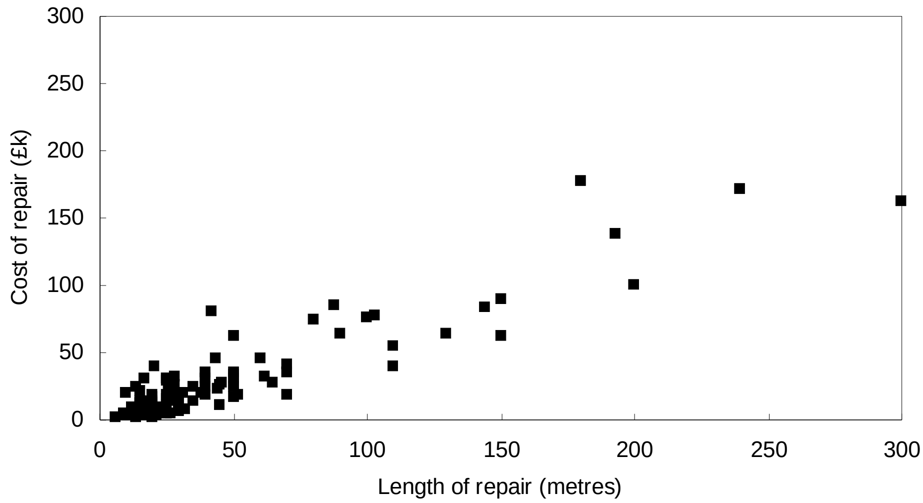
Regression equation takes the form;
*Repair cost (£k) = Constant + Coefficient*Repair Length (m)*

correlation is still very good, and the regression equation is shown in Table 2. The average weighted cost of a repair at 1995 prices is £805 per metre length.

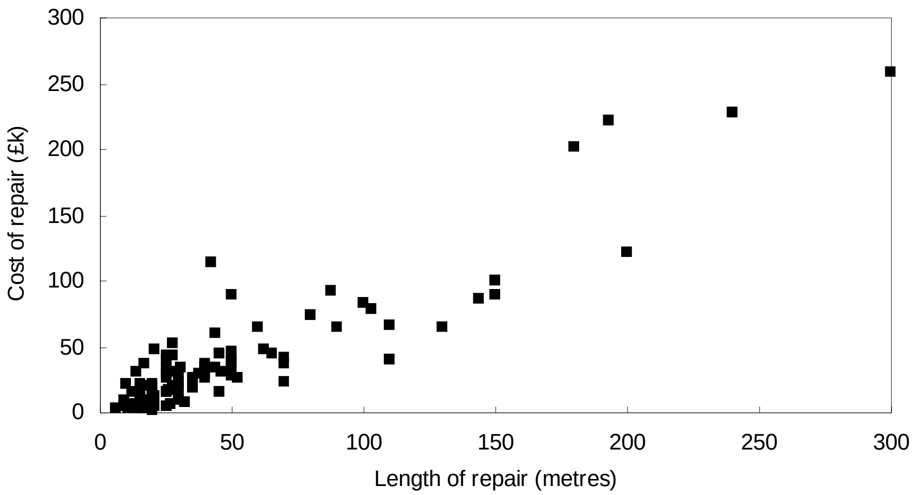
Because of the good correlation between repair cost and length, the costs can be normalised by dividing by the length to give the cost per metre run. This approach has been used in the remainder of this report. The cost of repairs seems to be almost independent of the height.

Repair costs (in £/metre) do not show much variation with time. When the costs are adjusted to 1995 prices, there is a slight downward trend with time. However, the variation in costs within each year is considerably greater than that between years.

In most cases, only the total cost of the repairs carried out by contractors was available, and this figure has been used in the preceding analyses. In a total of 19 cases, information was available on the costs of traffic management. This ranged from 0.3% of the total cost to 11.5%, with an average of 7.3%. In many cases traffic management costs are small, especially where access is possible from the foot of the embankment. Where access is required from the top of an embankment or at the foot of a cutting slope, closures of the hard shoulder and lane 1 may be necessary, and the higher costs are associated with these scenarios. In most cases, slope repairs were carried out in batches of up to 10 repairs as a single contract, especially



(a) Unadjusted prices



(b) Costs at November 1995 prices

Figure 4 Repair cost vs length

in counties such as Essex and Cambridgeshire where failures are most common. In some cases slope repairs were carried out as part of major maintenance contracts, eg. Lincolnshire and Kent. Occasionally single repairs were carried out where there was an imminent risk to the carriageway, or in areas where slope failures were not common, such as Cumbria and Warwickshire. One repair on the M42 in Warwickshire, which involved a hard shoulder and lane 1 closure, was carried out entirely during night shifts to minimise delays to traffic.

Costs for site investigation, design of remedial measures and supervision of construction were available for only 12 cases. Costs ranged from 5.2% to 30.6% of the total contractors costs, with an average of 11.3%. The wide range reflects the amount of investigation and design work required; frequently, no investigation is carried out and a standard design is used, especially where failures are common. The supervision costs are not included in the total costs used in the analyses; these are based purely on the contractor's costs. The actual cost of the repairs will thus be higher than the figures used here, because of supervision and client management costs. However, there is insufficient information to allow these costs to be quantified.

No information was available on costs for traffic delays due to slope failure repairs.

2.2.4 Overall costs of remedial earthworks

2.2.4.1 Local road maintenance expenditure on earthwork repair

Local roads are those which are the responsibility of local highway authorities and so exclude trunk roads and motorways.

Reports are available which contain information on local road maintenance expenditure by local authorities in England for the financial years 1985/86 to 1994/95, and Wales for the years 1987/88 to 1994/95. Each year, maintenance expenditure data are obtained from the Maintenance Outturn Form (MOF) completed by local authorities and returned to the Department of the Environment, Transport and the Regions (DETR). The MOF provides expenditure on some twenty one standard heads of account, under the broad headings of structural, routine and winter maintenance. Remedial earthworks is one of the headings under structural maintenance and is defined as ‘The repair of earth slips and the provision of any necessary drainage and new retaining systems. Anchors, walls, soil stabilisation and similar works are included’. These data have been published in full by DETR and its predecessors every year from 1985/86 to 1994/95, and extracts and brief summaries have also appeared as contributions to more general publications. The reports are intended to be a useful compendium of summary statistics, showing trends in key categories of expenditure. Unfortunately, this type of detailed data collection is no longer carried out.

Throughout the reports, data relate to expenditure on all classes of local road, ie. principal and non-principal roads are grouped together. The data can be expressed at constant prices using the Highways Maintenance Price Index (HMPI) (Department of Transport, 1995). Data on remedial earthworks for England have been collected since 1982/83, but data for Welsh local authorities were first collected in 1987/88. Similarly, data for individual Metropolitan Districts and London Boroughs have only been available since the abolition of the Metropolitan County Councils and the Greater London Council in April 1986. The data, adjusted to 1993/94 prices, are shown on Figure 5. The increase in costs from 1987/88 may be due at least in part to the inclusion of the Welsh data at that time. Expenditure peaked at £6.6 million in 1990/91, and stood at £5.1 million in 1994/95, the last year for which statistics are available.

2.2.4.2 Motorway and trunk road maintenance expenditure on earthworks

The central records for the expenditure on motorway and trunk roads has in recent years become even more unreliable than the local road records. The Regional Offices of the DETR were only returning about 60 per cent of the TR121A forms used in collecting the data. The form TR121A is the means by which the Directorate of Statistics collected information from the Regional Offices. The Regional Offices themselves used Appendices A and B of HA 48 ‘Maintenance of Highway Earthworks and Drainage’(DMRB 4.1.3) to procure expenditure on repairs but these are neither collected centrally nor analysed locally.

The deflator used by the DETR to adjust expenditure on motorway and trunk roads is the ‘Road construction tender price index’. However, these indices are for large construction contracts of £1 million or over, and are not really suitable for maintenance of earthworks expenditures. The HMPI has therefore been applied to adjust expenditure to 1993/94 prices, this being the last year for which data are available. The adjusted prices are shown graphically on Figure 5. It can be seen that there is a rapid increase in expenditure from 1989/90, rising to £11.6 million in 1993/94. It is of the utmost importance that data of this sort continue to be collected, accurately and comprehensively, in order to monitor the condition of earthworks. However, with the reorganisation of local authorities, compulsory competitive tendering for maintenance contracts and the rise of DBFO maintenance contracts all leading to regular changes in the Maintaining Agents for any one area, it is likely that reliable data will be even harder to obtain in the future.

Even with these incomplete data, it is evident that significant sums are being spent on remedial earthworks every year, especially in areas of overconsolidated clays such as Cambridgeshire, Essex and Hertfordshire. The data for individual repairs suggest that even with little or no new road building there will still be a large number of slips on existing roads for a number of years. The importance of establishing the relative costs of construction and maintenance for different engineering solutions by means of a whole life cost model is thus apparent.

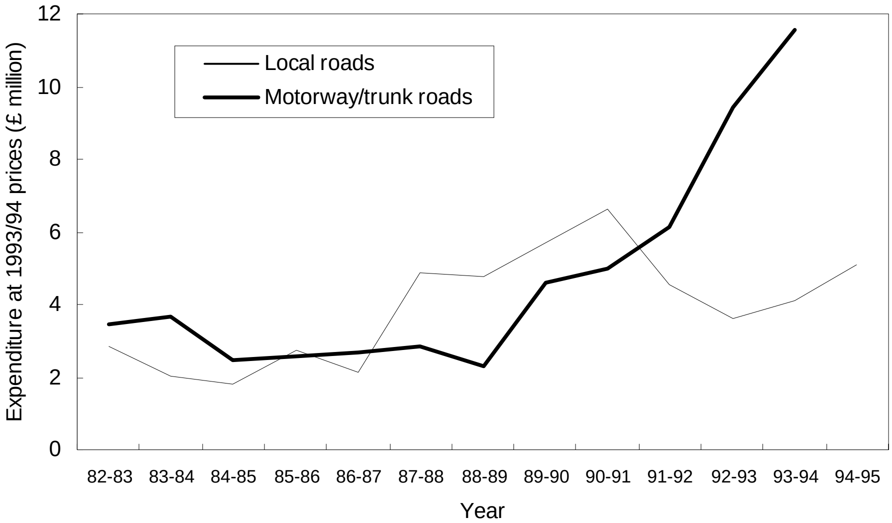


Figure 5 Variation of remedial earthworks expenditure with time

3 Whole life costing

3.1 General

Whole life costing is an economic technique whereby the overall cost of an asset can be computed over the whole of its operational life instead of on the basis of capital cost only. It is normally used as a method for comparing various options at an early stage in the life of a project, to enable a balanced decision to be made on which option should be preferred. It can also be used to optimise maintenance strategies for existing assets. Generally, the option with the lowest whole life cost would be preferred, although it may not have the lowest capital cost.

Whole life costing is a technique which has been used increasingly on construction projects since the 1960s. In America, the oil crises of the 1970s stimulated the use of whole life costing to improve the energy conservation of buildings (Kirk and Dell'Isola, 1995). Whole life costing is now required for most building projects by federal and state legislation and is widely used in the defense procurement and health industries in the UK and America (Ferry and Flanagan, 1991). It has also been applied to highways, particularly to pavements and structures (Robinson, 1993; Abell, 1989 & 1995).

The principle of whole life costing is to calculate all the costs associated with a project throughout its life to a common base so that comparisons can be made between options. This is done by discounting all the anticipated costs, calculated at present day prices, by a factor which takes account of the time from the start of the project to when the expenditure would be incurred. The discounted costs are then summed to give the *net present cost (NPC)* of the asset. This may be defined as 'the sum of money which would need to be set aside today to meet all the eventual costs, both present and future, after allowing for the accumulation of interest on that part of it intended for future commitments' (Ferry and Flanagan, 1991). NPC is calculated by the following formula:

(1)

Where N = Period of analysis (years)
C_t = Estimated cost in year t
r = Discount rate

The NPC is not a fixed sum for any given asset; it depends on the time period chosen for the analysis and the discount rate selected, as well as the estimated costs. In general, for a shorter time period, the estimated costs are likely to be more accurate, and the discount rate is more likely to be appropriate. Ferry and Flanagan (1991) state that whole life costing is well suited to assets with a relatively short life and high recurring costs - eg. plant or machinery with high energy consumption and maintenance costs. For longer time periods, cost estimates are likely to be less accurate, and the discount rate eventually reduces all costs to negligible levels. Ferry and Flanagan (1991) suggest an upper limit of 20 to 25 years for whole life costing of capital projects, with a residual value allocated to the asset in recognition of its usefulness beyond this time. However, the whole life costing approach is well suited to road pavements, which have a formalised maintenance procedure, high recurrent costs and a long evaluation period (Robinson, 1993); a 40 year evaluation period is routinely used in TRL pavement models such as COMPARE (Abell, 1995).

Whole life costing is an economic tool, and should be used with caution by engineers. The apparent simplicity of the NPC equation should not blind users to the assumptions on which it is based, which are not obvious to the non-economist. Some of these assumptions are discussed by Ferry and Flanagan (1991) and Dale (1993). In particular, the choice of discount rate and the question of ownership of costs require consideration.

The discount rate, r is a method of determining the time value of money. Due to the effects of interest rates, a sum of money invested today will increase in value with time. Since the anticipated costs during the lifetime of the asset are calculated at current prices, the costs need to be discounted to take account of the interest earned on the assumption that a sum equal to the NPC of the asset is invested at the start of the project. The discount rate is defined by Ferry and Flanagan (1991) as,'the minimum acceptable rate of return for the company'. This will vary depending on the owner of the asset. For Treasury-funded projects, a discount rate of 8% is normally applied (eg. DMRB 1.2.1), based on the value of interest rates on secure fixed-interest investments such as Treasury bonds or gilts. However, a private developer raising money to construct an office block might require a much higher return on capital in order to satisfy the banks; Dale (1993) suggests 35% might be typical for such a scenario. A consortium bidding for a DBFO contract may be working to a figure somewhere between these extremes. When evaluating PFI submissions, the Treasury requires Departments to evaluate them using a discount rate of 6%.

The value of r has a major effect on the results of the NPC calculations. A high value of r will favour projects with low initial capital costs, whereas a low discount rate will favour options with low maintenance costs. In a situation where whole life costing is being used to assess different options, with different parties involved at the construction and maintenance stages, it is important that an appropriate discount rate is agreed at the outset.

The situation is further complicated if inflation is considered. The effect of inflation is the opposite to that of interest rates, in that it decreases the value of money with time; hence the value of a pound in 1990 is less than it was in 1970. Inflation is unpredictable, and is not included in many whole life cost analyses. Individual cost items should be assessed, and if they are expected to change faster or slower than the general rate of inflation they can be adjusted accordingly (Ferry and Flanagan, 1991). However, if it is desired to allow for inflation, the discount rate can be modified to give the 'net of inflation discount rate', ndr, as follows (Dale, 1993):

(2)

The effect of using ndr rather than r is to reduce the discount rate, thus tending to favour options with low maintenance costs. Given the difficulty of predicting inflation rates, ndr should only be used for analyses with a time period of a few years.

A further problem with the application of whole life cost analysis is that costs at different stages of an asset's life cycle are frequently borne by different organisations, or different departments within the same organisation; construction and maintenance are examples of this trend. Each organisation will wish to minimise the impact of the project on its own budget, regardless of the best overall solution.

This leads on to the question of which costs should be included in a whole life cost analysis and how they should be calculated. Highly complex models can be created for large assets such as major buildings or highway schemes, allowing for a wide range of construction, operational, maintenance and disposal costs. However, detailed cost databases may not be necessary where the aim of the analysis is a general assessment of various options (Ferry and Flanagan, 1991). Given the uncertainties involved in the analysis, excessive effort in the estimation of all conceivable costs is seldom justified. The accuracy of the cost estimates should not be greater than that of the analysis as a whole. It is more important to have approximate estimates of all the main cost items than highly detailed analyses of only a few of them.

For publicly funded projects, factors such as taxation and VAT are not normally included in whole life cost analyses. However, for private companies these factors may have a significant effect on the costs, and items such as corporation tax and capital allowances are commonly included in the cost estimates. As with the choice of discount rate, this may result in a private company coming to a different conclusion on the best option for a project from that reached by a government department, though both bodies carried out whole life cost analyses on the same range of options. The results obtained from a whole life cost analysis are heavily dependent on the perspective of the organisation for whom the analysis is being carried out. The relevant information on discount rate and costs included in the analysis should always be given with the results, so that an objective assessment can be made.

Because of the numerous factors which can affect the results of the analysis, a number of calculations are normally carried out to cover the likely range of the parameters and establish the sensitivity of the model. An assessment of the various options can then be made. It is not possible to determine whether the difference between options is statistically significant. However, US Federal Government departments consider that analyses are 'indeterminate' if they show a difference of less than 10% between alternatives (Ferry and Flanagan, 1991). This provides a useful 'rule-of-thumb' for assessing the results of whole life cost analyses.

From the above, it may be concluded that whole life costing is a useful tool for evaluating the economic consequences of a number of options for a project over the whole of its working life, but that care is needed when selecting the parameters to ensure that the analysis is appropriate to the situation. Whole life costing can reduce the emphasis on capital cost as the determining factor in selecting an option; 'it is an auditable financial ranking system for mutually exclusive alternatives which can be used to promote the desirable and eliminate the undesirable in a financial environment' (Dale, 1993). As such, it is ideally suited to publicly-funded projects where accountability is very important. With the increasing involvement of private companies in the construction, operation and maintenance of infrastructure which was formerly publicly owned, it should be realised that these companies may use significantly different parameters from those appropriate to a public body, leading to different results from a whole life cost analysis.

3.2 Application to highways

Work on whole life cost analysis of highway projects has been carried out since the 1960s at TRL and is summarised by Robinson (1993). The models have become increasingly complex, and have focused mainly on road pavements, where there is a large database of information on costs and rates of deterioration, culminating in the development of the computer model COMPARE (Abell, 1995). Work has also been undertaken on whole life costing of highway bridges, which also have fixed maintenance procedures. Work is currently in progress on a whole life cost model for the highway network which aims to combine information from structures, pavements and earthworks to assess alternative maintenance options for managing the network and to assess the return from investment in road infrastructure.

4 Whole life cost model for earthworks slopes

4.1 Objectives

The objectives of the whole life cost model for earthworks slopes are listed below:

i to enable a comparison of different engineering solutions to be made for earthworks slopes in terms of whole life costs for any given section of earthworks;

ii to establish the most economic engineering solutions for typical earthwork sections for a range of soil types and land prices by means of whole life cost analyses; and

iii to enable an estimate to be made of the residual costs of earthworks slope failures beyond the handover of a DBFO scheme to the public sector 30 years after construction.

4.2 Scope

Surveys of the motorway network have shown that, for certain soil types, there are significant levels of slope failures in both cuttings and embankments (Perry, 1989; Andrews, 1990). These are most common in overconsolidated clay formations such as the Gault Clay; in such soils, slope angles as low as 1:5 are necessary to reduce the level of failure to less than 1% in 25 years (Perry, 1989). Because of a desire to minimise land take, and hence land acquisition costs, most motorway and trunk road earthworks have been constructed at much steeper slopes, typically 1:2 to 1:3. As a result, ongoing problems with slope failures have occurred in these materials, requiring expenditure on repairs. This expenditure has increased significantly during the 1990s and is a source of concern to the Highways Agency.

The present project was conceived as a means of balancing the increased costs of construction and land acquisition for flatter slopes against the increased costs of slope repairs for steeper slopes. By using a whole life cost model, both the capital and maintenance costs can be taken into account and comparisons can be made between different options on a rational basis. The study covers all the soil types identified as having high rates of slope failure and a range of prices for agricultural land representative of England and Wales. Rock slopes, and soils with low rates of failure are not included; however, if the rate of failure is known, the model can be used to calculate whole life costs for a range of engineering solutions and land prices.

The model is designed mainly for new construction, to allow selection of the most economic whole life engineering solution. This can be carried out for any given section of earthwork, soil type and land price. The model has also been used to generate comparative whole life costs for a range of engineering solutions, soil types and land prices for two typical earthworks sections; a 100 m long embankment with a maximum height of 10.0 m, and a 100 m long cutting with a maximum depth of 10.0 m. The results are given in Tables 3 to 8, which may be used as rapid guides to the most economic solution, and are discussed in chapter 6.

An increasing number of highway schemes are being let as Design, Build, Finance and Operate (DBFO) contracts. These contracts are generally for a period of 30 years, after which the highway will be handed back to the Government. It is therefore important for HA to be able to estimate the likely maintenance costs associated with the proposed earthworks design in the period after the highway has been handed back to the Government. Using a whole life cost analysis, these costs are likely to be negligible regardless of the actual rate of failure because of the effect of the discount factor $1/(1+r)^t$ at high values of t. However, the residual rate of failure and the present-day costs of the associated repairs can be estimated from the information on failure rates and repair costs. This will allow HA to assess DBFO tenders to ensure that the Government is not left with excessive maintenance costs when the scheme is handed back in 30 years time.

4.3 Assumptions

The model used for the net present cost calculations is given by the following equation:

(3)

(4)

where

C_0	=	Construction Cost (C_C) + Land Acquisition Cost (C_L) (5)
C_1 ... C_N	=	Maintenance Cost in year t
	=	Percentage failure in year t (P_t) x Length of earthwork (L) x Cost of repair (R) (6)
r	=	Discount rate
N	=	Length of study period, in years

The various items are discussed in more detail in the following sections.

4.3.1 Construction costs

These are taken as the costs for constructing the earthworks slope, from the edge of the hard shoulder to the toe of the embankment or the top of the cutting as shown on Figure 6. The costs of constructing the embankment or excavating the cutting above or below the area of the road pavement and hard shoulder is not included; this area has to be constructed irrespective of the engineering solution chosen for the slopes, hence it is not appropriate to include it in an assessment of the slope options. If the central area was included, the associated construction and land acquisition costs would dominate the calculations. Slope failures only affect the shoulders, hence earthworks maintenance costs are only incurred on the slopes, so to enable a fair comparison of construction and maintenance costs to be made, only the slopes are considered in this model.

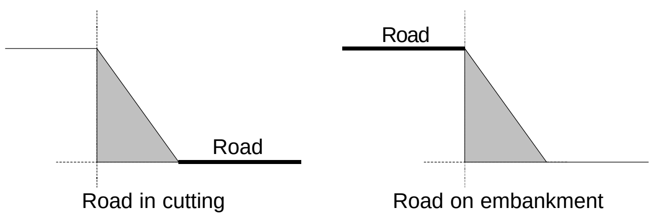


Figure 6 Definition of earthworks slopes for whole life cost model

Calculation of the construction costs may be carried out by creating a scaled down bill of quantities for the earthworks section and using appropriate rates. The calculations of volumes and areas may be carried out by taking cross sections at intervals along the section and summing the quantities. The computer programme allows for up to 15 sections to be specified for each earthwork considered. Given the uncertainties in predicting the rates of slope failure, an excessive degree of accuracy in the quantities is not required. The items may be taken from the Bill of Quantities for Highway Works (MCHW4) or the Civil Engineering Standard Method of Measurement,

Table 3 Results of Net Present Cost analysis for Gault Clay

Land price £/acre	*Slope type*	*Slope angle*	*Capital cost £k*	*NPC (30) £k*	*NPC (60) - NPC (30) / NPC (30) %*
1000	Embankment	1 in 2	3.9	11.5	2.6
	Embankment	1 in 3	5.8	13.4	2.2
	Embankment	1 in 5	9.6	9.9	0.0
	Cutting	1 in 2	1.9	7.1	15.5
	Cutting	1 in 3	2.8	7.9	15.2
	Cutting	1 in 5	4.5	4.8	0.0
2000	Embankment	1 in 2	4.2	11.7	3.4
	Embankment	1 in 3	6.2	13.7	2.9
	Embankment	1 in 5	10.2	10.5	1.0
	Cutting	1 in 2	2.1	7.3	16.4
	Cutting	1 in 3	3.1	8.3	14.5
	Cutting	1 in 5	5.1	5.4	0.0
3000	Embankment	1 in 2	4.4	12.0	2.5
	Embankment	1 in 3	6.5	14.1	2.1
	Embankment	1 in 5	10.8	11.1	0.9
	Cutting	1 in 2	2.4	7.5	16.0
	Cutting	1 in 3	3.5	8.7	12.6
	Cutting	1 in 5	5.7	6.0	0.0
4000	Embankment	1 in 2	4.7	12.2	3.3
	Embankment	1 in 3	6.9	14.5	2.1
	Embankment	1 in 5	11.4	11.8	0.0
	Cutting	1 in 2	2.6	7.8	15.4
	Cutting	1 in 3	3.9	9.0	13.3
	Cutting	1 in 5	6.4	6.6	1.5

Table 4 Results of Net Present Cost analysis for Oxford Clay

Land price £/acre	*Slope type*	*Slope angle*	*Capital cost £k*	*NPC (30) £k*	*NPC (60) - NPC (30) / NPC (30) %*
1000	Embankment	1 in 2	3.9	7.5	4.0
	Embankment	1 in 3	5.8	9.4	2.1
	Embankment	1 in 5	9.6	9.9	0.0
	Cutting	1 in 2	1.9	4.0	5.0
	Cutting	1 in 3	2.8	4.8	6.3
	Cutting	1 in 5	4.5	4.8	0.0
2000	Embankment	1 in 2	4.2	7.7	3.9
	Embankment	1 in 3	6.2	9.7	3.1
	Embankment	1 in 5	10.2	10.5	1.0
	Cutting	1 in 2	2.1	4.2	7.1
	Cutting	1 in 3	3.1	5.2	5.8
	Cutting	1 in 5	5.1	5.4	0.0
3000	Embankment	1 in 2	4.4	8.0	3.8
	Embankment	1 in 3	6.5	10.1	3.0
	Embankment	1 in 5	10.8	11.1	0.9
	Cutting	1 in 2	2.4	4.4	6.8
	Cutting	1 in 3	3.5	5.6	5.4
	Cutting	1 in 5	5.7	6.0	0.0
4000	Embankment	1 in 2	4.7	8.2	3.7
	Embankment	1 in 3	6.9	10.5	2.9
	Embankment	1 in 5	11.4	11.8	0.0
	Cutting	1 in 2	2.6	4.7	6.4
	Cutting	1 in 3	3.9	5.9	5.1
	Cutting	1 in 5	6.4	6.6	1.5

Table 5 Results of Net Present Cost analysis for Reading Beds

Land price £/acre	*Slope type*	*Slope angle*	*Capital cost £k*	*NPC (30) £k*	*NPC (60) - NPC (30) / NPC (30) %*
1000	Embankment	1 in 2	3.9	13.3	2.3
	Embankment	1 in 3	5.8	15.1	2.6
	Embankment	1 in 5	9.6	10.0	0.0
	Cutting	1 in 2	1.9	4.7	6.4
	Cutting	1 in 3	2.8	5.6	3.6
	Cutting	1 in 5	4.5	4.9	0.0
2000	Embankment	1 in 2	4.2	13.5	3.0
	Embankment	1 in 3	6.2	15.5	2.6
	Embankment	1 in 5	10.2	10.6	0.0
	Cutting	1 in 2	2.1	5.0	4.0
	Cutting	1 in 3	3.1	6.0	3.3
	Cutting	1 in 5	5.1	5.5	0.0
3000	Embankment	1 in 2	4.4	13.7	2.9
	Embankment	1 in 3	6.5	15.9	1.9
	Embankment	1 in 5	10.8	11.2	0.0
	Cutting	1 in 2	2.4	5.2	5.8
	Cutting	1 in 3	3.5	6.3	4.8
	Cutting	1 in 5	5.7	6.1	0.0
4000	Embankment	1 in 2	4.7	14.0	2.9
	Embankment	1 in 3	6.9	16.2	2.5
	Embankment	1 in 5	11.4	11.8	0.0
	Cutting	1 in 2	2.6	5.5	3.6
	Cutting	1 in 3	3.9	6.7	3.0
	Cutting	1 in 5	6.4	6.7	0.0

Table 6 Results of Net Present Cost analysis for London Clay

Land price £/acre	*Slope type*	*Slope angle*	*Capital cost £k*	*NPC (30) £k*	*NPC (60) - NPC (30) / NPC (30) %*
1000	Embankment	1 in 2	3.9	8.1	2.5
	Embankment	1 in 3	5.8	10.0	2.0
	Embankment	1 in 5	9.6	9.9	0.0
2000	Embankment	1 in 2	4.2	8.3	3.6
	Embankment	1 in 3	6.2	10.3	2.9
	Embankment	1 in 5	10.2	10.5	1.0
3000	Embankment	1 in 2	4.4	8.6	2.3
	Embankment	1 in 3	6.5	10.7	1.9
	Embankment	1 in 5	10.8	11.1	0.9
4000	Embankment	1 in 2	4.7	8.8	3.4
	Embankment	1 in 3	6.9	11.1	1.8
	Embankment	1 in 5	11.4	11.8	0.0

Table 7 Results of Net Present Cost analysis for Lower Lias

Land price £/acre	Slope type	Slope angle	Capital cost £k	NPC (30) £k	NPC (60) - NPC (30) / NPC (30) %
1000	Embankment	1 in 2	3.9	12.2	0.04
	Embankment	1 in 3	5.8	14.0	0.04
	Embankment	1 in 5	9.6	9.9	0.0
	Cutting	1 in 2	1.9	6.9	5.8
	Cutting	1 in 3	2.8	7.7	5.2
	Cutting	1 in 5	4.5	4.9	0.0
2000	Embankment	1 in 2	4.2	12.5	0.04
	Embankment	1 in 3	6.2	14.5	0.03
	Embankment	1 in 5	10.2	10.6	0.0
	Cutting	1 in 2	2.1	7.1	5.6
	Cutting	1 in 3	3.1	8.1	4.9
	Cutting	1 in 5	5.1	5.5	0.0
3000	Embankment	1 in 2	4.4	12.7	0.04
	Embankment	1 in 3	6.5	15.0	0.03
	Embankment	1 in 5	10.8	11.2	0.0
	Cutting	1 in 2	2.4	7.4	5.4
	Cutting	1 in 3	3.5	8.5	4.7
	Cutting	1 in 5	5.7	6.1	0.0
4000	Embankment	1 in 2	4.7	13.0	0.04
	Embankment	1 in 3	6.9	15.2	0.03
	Embankment	1 in 5	11.4	11.7	0.01
	Cutting	1 in 2	2.6	7.6	5.3
	Cutting	1 in 3	3.9	8.9	4.5
	Cutting	1 in 5	6.4	6.7	0.0

NB: for cutting, Lower Lias is with Middle Lias

Table 8 Results of Net Present Cost analysis for Glacial Till

Land price £/acre	Slope type	Slope angle	Capital cost £k	NPC (30) £k	NPC (60) - NPC (30) / NPC (30) %
1000	Embankment	1 in 2	3.9	6.2	6.5
	Embankment	1 in 3	5.8	8.0	5.0
	Embankment	1 in 5	9.6	9.8	1.0
	Cutting	1 in 2	1.9	2.8	7.1
	Cutting	1 in 3	2.8	3.7	5.4
	Cutting	1 in 5	4.5	4.8	0.0
2000	Embankment	1 in 2	4.2	6.4	6.3
	Embankment	1 in 3	6.2	8.4	4.8
	Embankment	1 in 5	10.2	10.5	0.0
	Cutting	1 in 2	2.1	3.1	6.5
	Cutting	1 in 3	3.1	4.1	4.9
	Cutting	1 in 5	5.1	5.4	1.9
3000	Embankment	1 in 2	4.4	6.7	6.0
	Embankment	1 in 3	6.5	8.8	4.5
	Embankment	1 in 5	10.8	11.1	0.0
	Cutting	1 in 2	2.4	3.3	6.1
	Cutting	1 in 3	3.5	4.4	4.5
	Cutting	1 in 5	5.7	6.0	1.7
4000	Embankment	1 in 2	4.7	6.9	5.8
	Embankment	1 in 3	6.9	9.1	5.5
	Embankment	1 in 5	11.4	11.7	0.0
	Cutting	1 in 2	2.6	3.6	2.8
	Cutting	1 in 3	3.9	4.8	4.2
	Cutting	1 in 5	6.4	6.6	1.5

NB: for embankment, Glacial Till is with Lower and Middle Lias

Third Edition (CESMM3). Standard published rates, such as those given in the CESMM3 Price Database 1996/97 (Harris, 1996), or site specific rates may be used to calculate the costs. CESMM was chosen for the computer programme as default rates are publicly available from the CESMM3 Price Database 1996/97 (Harris, 1996).

The construction costs used for the tables of comparative whole life costs for different soil types (Tables 3 to 8) were generated using bill items from CESMM3 and rates from the CESMM3 Price Database 1996/97. Typical sections of embankment and cutting 10.0 m in height and 100 m in length were considered (note that each section is for one side of the carriageway only). The height and length were chosen for ease of calculation, and to ensure that the output values contained a suitable number of figures.

The volume of the earthworks and the area of the slope face for the cases in Tables 3 to 8 were calculated on the basis of one cross-section at half the maximum height, on the assumption that the earthwork rose evenly from zero to the maximum height at mid-length, then decreased evenly to zero at the end of the section. Real earthwork sections have more complex geometry and may require a greater number of cross-sections to establish the quantities, but for this idealised scenario one section was judged sufficiently accurate.

For cuttings and embankments, the following items from CESMM3 were used:

cutting
- E220 excavation of material other than topsoil, rock or artificial hard material.
- E512.02 trimming of excavated surface in material other than topsoil, rock or artificial hard material inclined at an angle of 10° - 45° to the horizontal.

embankment
- E623.02 non-selected excavated material other than topsoil or rock from excavation at 500 m distance.
- E712.02 trimming of filled surface in material other than topsoil, rock or artificial hard material inclined at an angle of 10° - 45° to the horizontal.

No allowance has been made for double-handling, stockpiling, disposal off site or foundation treatment such as sand drains or excavation of unacceptable material. The costs are based on the assumption of material being excavated from a cutting in one part of the site and placed immediately in an embankment within 500 m.

Costs are calculated using the rates in the CESMM3 Price Database 1996/97. These rates reflect the cost to the contractor of carrying out the activities, so an allowance of 10% for profit has been included. The rates do not cover general items, head office costs and VAT, and no allowance has been made for these items.

4.3.2 Land acquisition costs

These costs are calculated on the basis of the area occupied by the slope, and do not include the area above or beneath the carriageway and hard shoulder or areas of landscaping.

The reasons for this are the same as those given for construction costs in the previous section. The area is calculated as the length of the section times half the width of the slope at maximum height. This assumes that the area of land acquired for the highway will follow the shape of the earthworks slope, varying in width with the height of the slope. If the land take does not follow the outline of the earthworks, errors will be introduced by this assumption. The worst case scenario would be where a corridor parallel to the centre-line was acquired, with the width determined by the maximum height of the earthwork. This would give an area exactly twice that of the example above.

Land prices are highly variable, depending on the existing use of the land, the region of the country and specific market conditions. The range of values used in the comparative tables are based on typical values for agricultural land in different regions of England and Wales given in the Property Market Report - Autumn 1994 published by the Valuation Office (1994). In this survey, the average value for mixed farmland in England and Wales was £2180/acre. Site specific values of land price can be entered into the model.

4.3.3 Maintenance costs

For the purposes of the model, maintenance costs for earthworks are defined solely as costs connected with the repair of slope failures. Routine maintenance activities such as grass cutting and litter collection are not included. These will show some variation with the engineering solution chosen; flatter slopes mean more grass to cut, but may make it easier to cut than very steep slopes.

The maintenance costs are defined as the percentage failure per year multiplied by the length of the earthwork and the cost of the repair. This assumes that the failures are repaired in the same year in which they occur. In practice, this does not always happen. Slope failures which threaten the carriageway or property adjacent to the highway are generally repaired within a year because the consequences of not repairing them would be very serious. However, most slope failures do not pose an immediate threat of this magnitude. There is usually a delay while the slip is assessed, Forms A and B of HA48 (DMRB 4.1.3) are completed by the Maintaining Agent and approved by the Highways Agency, and funds are allocated for the work. This process can take several years; the time from failure to repair for the 106 cases in the slope repair database ranged from less than 1 year up to 12 years, with an average of 2 years. The model includes an option to delay the repair by a specified number of years, up to a maximum of 5 years; this aspect is considered in more detail in section 4.3.4. However, the comparative tables were calculated on the basis of the failure and repair taking place in the same year. The effect of introducing a delay period is discussed in chapter 6.

Two main methods of slope repair are employed; replacement with granular material, and reuse of the failed material with the incorporation of geogrids. The cost was found to be closely related to the length of the repair. The cost of the two methods was very similar; the average cost for granular replacement was £841/m length at 1995 prices, while that for geogrid reinstatement was £791/m length. The difference between the two means was not statistically significant, however, so the overall weighted mean of £805/m length was used for calculating the values in the comparative tables. In practice, granular replacement is generally used where granular materials are readily available and relatively cheap, generally in the north and west of England and Wales, whereas geogrid reinstatement is more common in the south and east where granular materials are scarce and expensive.

The largest unknown factor in the calculations is the rate of slope failure. This has been discussed in section 2.1.2. From the motorway slope condition survey, Perry (1989) produced tables giving maximum slope angles to restrict the percentages of failure to below 1% within 25 years of construction for a range of soil types and slope heights for cuttings and embankments. This rate provides a default value of slope failure rate for slopes at or below the angles stated in the tables. The original data used by Andrews (1990), and the data from the slope repair database, were examined to develop quantitative prediction methods for slopes which exceed the limiting values.

The variability between the different soil types is so great that it has proved difficult to develop a suitable model to describe them. A guide to the general distribution of slope failures with age is given by the data in the slope repair database, shown on Figure 2. This shows a low number of failures in the first 3 years, rising to a broad peak between 5 and 15 years with a gradual but irregular decline to the oldest recorded failures at 29 years. The data represent a number of soil types, a wide range of heights and both cuttings and embankments. This broad distribution was considered to be typical of the shape of the age/percentage failure curve for most soil types, though the position and height of the peak and the shape of the curve will vary between different soil types and, probably, between the same soil in different locations. A curve of this general shape can be described by a log-normal equation with three constants; one defining the age of the peak, the second defining the size of the peak, and the third defining the shape of the curve. The integral of the log-normal equation describes the cumulative percentage failure against age curve. This appeared to be a suitable model to use for the prediction of failure rate. The development of the predictive model for frequency of slope failure is described in Appendix A.

The original data used by Andrews (1990) and the Cambridge Northern Bypass data were examined and log-normal equations fitted to give the visual ‘best fit’ for the cumulative percentage failure against time graphs. The general shape of the log-normal and cumulative log-normal distributions are shown on Figure 7. The results for the various soil types are shown on Figure A12 to A26 and summarised on Table A2. The data for all slope height ranges were amalgamated to give an overall equation for each soil type. This allows rapid computation of the estimated percentage failure for any given earthwork section for any given time period. There is insufficient data to calculate equations for all height ranges for all soil types, and given the variability between soil types it is not

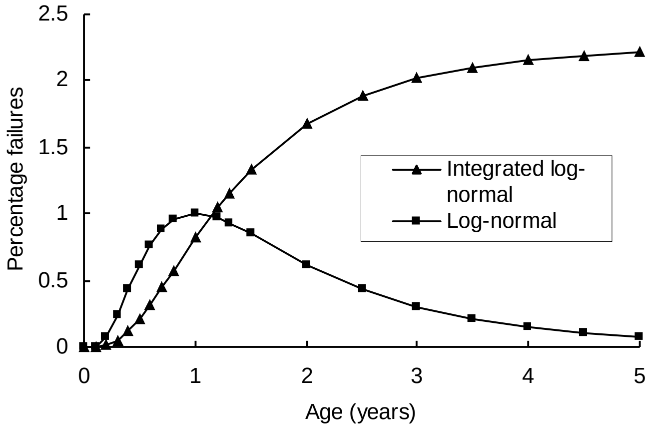


Figure 7 Plots of the log-normal and integrated log-normal distributions

considered worthwhile to add this extra factor into the calculations at this stage.

It is not possible to calculate statistical levels of significance for non-linear regression equations such as the log-normal distribution. However, a qualitative assessment of the reliability of the curves may be made by considering the number of observations on which they are based and the length of earthwork surveyed. This information is given in Table A2. A number of the equations are based on only three records of the percentage slope failure, and these equations must be regarded as particularly liable to error, especially where the length surveyed is short. The most reliable equation is for the Gault Clay on embankment, which is based on the comprehensive Cambridge Northern Bypass data.

The integral of the log-normal distribution is a useful equation because the total percentage which will fail - i.e. the total area under the curve - is given by the value of the function at infinity. This is also shown in Table A2. The percentage failure which the Government will have to deal with is therefore this value minus the value of the function at an age of 30 years, when the slope will be handed back by the DBFO contractor. The cost of this work, at current prices, is given by this difference in percentage multiplied by the length of the earthwork section and the average repair cost. In practice, the value of Net Present Cost (NPC) at 60 years has been used instead, and the residual cost is calculated as NPC_{60} minus NPC_{30} . This figure is the residual cost quoted in Tables 3 to 8. Given the many uncertainties in the model and the lack of failure data beyond 40 years, it was felt that extrapolation beyond 60 years was unsafe. However, it should be noted that the nominal design life for earthworks may be up to 120 years.

These equations should be used with great caution when predicting failure rates beyond the time period for which data are available. This is given in Table A2 and varies from less than 10 years up to 25 years. The predicted failure rates beyond these dates are based on the assumption that the rate of failure will follow a log-normal distribution with time. This appears to be the case for a number of soil types, particularly on embankment. However, for some cuttings the observed failure rates were still rising at the last data point; if these slopes were following a log-normal trend, they were either at or had not yet reached the peak of the distribution, and hence the predictions of future behaviour are particularly uncertain for these materials. The predictive equations for these materials allow for significant increases in the cumulative percentage failed with time (Figure A12 to A26), but should only be regarded as rough estimates. There is an urgent need for more data on the long term failure rates of highway earthworks slopes.

The ultimate percentage failed obtained from the predictive equations and shown in Table A2 is a function of the model and should be regarded as little more than an estimate. In the long term, significant changes in pore pressures may occur, leading to deviations from the empirical model, which effectively relates only to surface softening of the overconsolidated clays. Long term failures in clay cuttings and embankments are liable to be deep seated and would therefore be much more expensive to repair. Theoretical work on this topic has been carried out by the Geotechnical Consulting Group (1993). This aspect also requires further research.

The predictive equations have been developed for a total of 15 combinations of cuttings and embankments, single soil types and combinations of soils (Table A2). In total, only 9 soil types are included. These include most of the materials identified as having a high percentage of failure by Perry (1989). For soils for which no equation is given in Table A2, the equation for a similar soil may be used, eg. for Kimmeridge Clay the equations for Oxford Clay may be used. The default failure rate of less than 1 percent in 25 years may be used for a wide range of soil types at slope angles and heights not greater than those given in Tables 6, 7, 14, 15, 20, 21, 26 and 27 in Perry (1989). The above equations will cover most of the soil types likely to be encountered in England and Wales. If site specific data on failure rates are available, these should be used.

In conclusion, while equations have been developed to predict the rate of slope failure for use in the whole life cost model, it should be appreciated that there are many uncertainties associated with them, particularly when predicting more than 25 years after construction. These uncertainties limit the accuracy of the model. There is a need for further research to develop more reliable methods of predicting the rate of failure of highway earthworks. This should include more detailed analysis of existing data held by the Maintaining Agents in areas such as the M25 (London Clay) and for older motorways such as the M1. Ideally, the aim would be to produce a Quantitative Risk Assessment procedure which would produce an appropriate equation for any given earthworks scenario and soil type.

4.3.4 Other costs

There are several other possible sources of cost which have not been taken into account in the relatively simple model described above. Taxation and VAT have not been included; this is appropriate for a publicly funded project, but it should be appreciated that a private sector contractor would incorporate these factors, where relevant, in any whole life cost analysis.

No costs for ground investigation, design and supervision of construction have been included for either construction or maintenance, nor have costs associated with land acquisition and statutory procedures. The magnitude of these costs is difficult to estimate, and to apportion between the earthworks slopes and all the other aspects of the highway such as structures, pavement, the earthworks directly underlying the pavement, landscaping and so on. A limited amount of data on ground investigation, design and supervision costs was obtained for slope repairs during the collection of the slope repair database. Costs ranged from 5.2% of the slope repair costs to 30.6%, with an average of 11.3%. Investigation generally consists only of a visual inspection, and standard repair details are frequently used, so that the costs are limited to preparation of contract documents for a batch of 6 to 10 repairs, letting the contract and site supervision, which is generally on a part-time basis. Thus, while these associated costs are not known in detail for either construction or repairs, they are likely to be relatively small and should effectively cancel each other out.

A further factor which has not been considered is road user costs. These can be the dominant feature in road pavement models (Robinson, 1993; Abell, 1995), but are generally less significant for earthworks slopes. In many cases, the slope failures are accessed primarily from the toe of the embankment or the top of the cutting respectively, and the only traffic management measures required are advance warning signs and coning off the hard shoulder. These measures are not considered to cause any significant increase in user costs. In locations where access to the slip is only possible from the carriageway, it may be necessary to cone off lane 1 as well as the hard shoulder; on one such repair, the work was carried out entirely during night shifts, with the carriageway being reopened during the day, to minimise delays to traffic. In other cases, slope repairs are carried out at the same time as resurfacing work on the pavement, so no additional user costs are incurred due to the earthworks.

In general, slope failures do not impinge on the road pavement; they are normally confined to the slope face and are relatively shallow (Perry, 1989). However, if slope failures are left unrepaired they will gradually extend back up the slope until they start to undermine the hard shoulder or pavement. If a failure is allowed to progress to this extent, not only will it be larger and more expensive to repair, but it will entail lane closures with associated traffic management and road user costs. There are no exact data on how long it will take a failure to progress until it affects the carriageway; this will depend on where the failure occurs on the slope, how deep it is, and site specific factors such as broken drainage which will direct water onto the slope and accelerate the rate of movement. Some minor failures are judged not to be a threat to the carriageway or adjacent property and are never repaired, though they will be regularly monitored. The data from the slope repair database indicate that most failures which are repaired are treated within 4 years of the failure occurring.

If the model is to be used to optimise a maintenance strategy for a section of highway, incorporating earthworks, structures and the road pavement, then it would be necessary to introduce a limiting time period from slope failure to repair, which, if exceeded, would result in the failure affecting the carriageway. This would require immediate remedial action and would involve user costs due to lane 1 being coned off for the duration of the repair. It would seem reasonable to use 5 years as the default value for this limiting time period. The average length of an individual slope repair is about 30m, and it takes on average about 5 working days for a geogrid replacement repair. These figures, and the average cost, will increase if the failure extends to the carriageway; as an initial estimate, the size, time and cost of the repairs might double if the hard shoulder was undermined and had to be repaired. User costs for closing lane 1 would be incurred for 10 working days, and any costs for damaged services would also have to be included; these costs could be several orders of magnitude higher than the costs of a normal slope repair.

4.3.5 Discount rate

The standard Treasury rate of 8% has been used, with no allowance for inflation. However, the model allows other discount rates to be used where these are appropriate. A sensitivity analysis was carried out to assess the effects of varying the discount rate, and the results are presented in chapter 6.

5 Operation of the computer program

The computer program is called WLCslope version 1.0 and is in Visual Basic. Its operation is illustrated in a flow chart on Figure 8. The flow chart shows the routes which the user may take through the program and also the options available to the user at each stage. An overview of the operation of WLCslope is detailed below. More detailed descriptions of the different stages of the program can be seen in the User Manual. A worked example is shown in Appendix B.

5.1 Required user input

Earthworks details:
slope angle (as 1:... (V:H))
slope type (embankment or cutting)
soil type
earthwork length
maximum slope height

Costing details:
costing period
delay period
construction and repair costs (default values are available)
discount rate (default value available)

5.2 Program outputs

- The whole life cost - as net present cost (NPC) - of the earthworks over the costing period in graphical form.
- Capital cost, NPC for the costing period, NPC for 60 years and the residual cost (NPC_{60} - NPC_{30}) in tabular form.

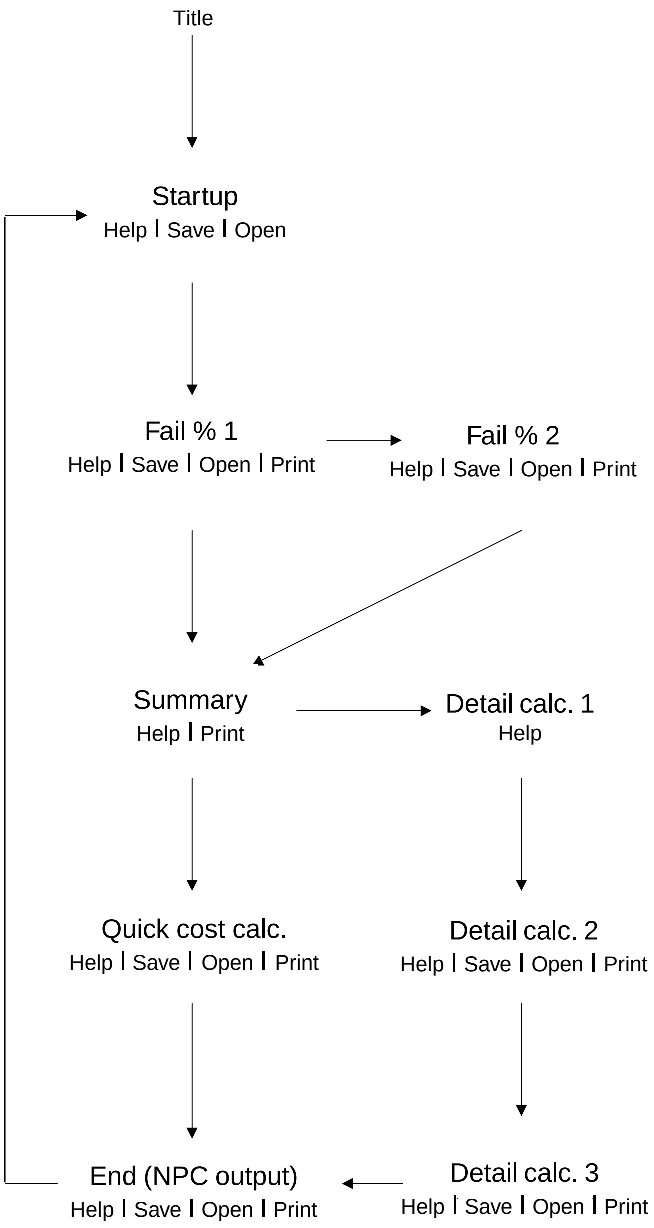


Figure 8 Flow chart for whole life cost model for earthworks slopes

5.3 Step by step guide

1 User input stage - The initial slope details are entered here.

2 Slope failure rate stage - The program will display the slope failure rates associated with the user's input data. The user can accept the given failure rate or, if new data are available, a user defined failure rate based on the log-normal distribution may be developed. Once the failure rate is either accepted or defined the summary page is displayed

3 Summary page - The program will request that the user chooses the calculation procedure to be followed for the slope geometry and costing.

4 The quick calculation procedure - The earthwork geometry and land take area will be calculated on the basis of an average section over the specified length. Once the slope geometry has been defined, the costs for land take and construction must be entered. Default values for the costs are available from the 'File' menu.

5 Detailed calculation procedure - WLCslope will request that the user enters the slope height at mid section and the section length for a number of slope sections. This will enable more precise slope geometry to be defined before the capital cost is calculated.

6 Net present cost analysis - WLCslope will combine the failure rate details for the defined earthwork with the costing details and carry out a NPC analysis to produce the discounted NPC over the specified time period.

7 Options - At the output stage the user can choose to run the program again (restart keeping output button), alter one or more of the input values, and compare the output. The program can be re-run up to 10 times allowing 10 sets of data to be compared. There are options to save the output data, save the output table, print the graph or print the table.

5.4 Output features

After each analysis WLCslope allows the user to save the data used to generate the graph of Net Present Cost against time. This enables the user to reproduce the output graphs within spreadsheet applications if required. The output table may also be saved to a file for later use within spreadsheet programs.

The printing options in WLCslope allow any of the graphs displayed to be printed along with any identifying text the user chooses to enter at the print stage. The output table, as it is displayed on the screen may also be printed.

6 Discussion

6.1 Soil type and slope angle

6.1.1 General

Net Present Cost analyses were carried out for six overconsolidated clays at a range of slope angles and land prices using a standard section 100 m in length and 10 m in height. Analyses were carried out for embankments and cuttings at slopes of 1:2, 1:3 and 1:5, and for land prices of £1000, £2000, £3000 and £4000 per acre. The slope angle of 1:5 represents the default rate of less than 1% failure in 25 years. The higher rates of failure based on the predictive equations described in chapter 4 apply to the 1:2 and 1:3 slopes. The capital costs, NPC_{30}, and residual costs $(NPC_{60} - NPC_{30})/NPC_{30}$ as a percentage for each analysis are given in Tables 3 to 8. Typical graphs showing the Net Present Cost against time for the three slope angles on embankment and cutting are shown on Figures 9 to 14. In all cases the discount rate was 8% and there was no delay period between failure and repair. The default values were used for construction and repair costs.

The six soil types for which the analyses were carried out are those for which most data on failure rates are available; Gault Clay, Oxford Clay, Reading Beds, London Clay (embankment only; no data on failure rates for cuttings), Lower Lias and Glacial Till ('Boulder Clay').

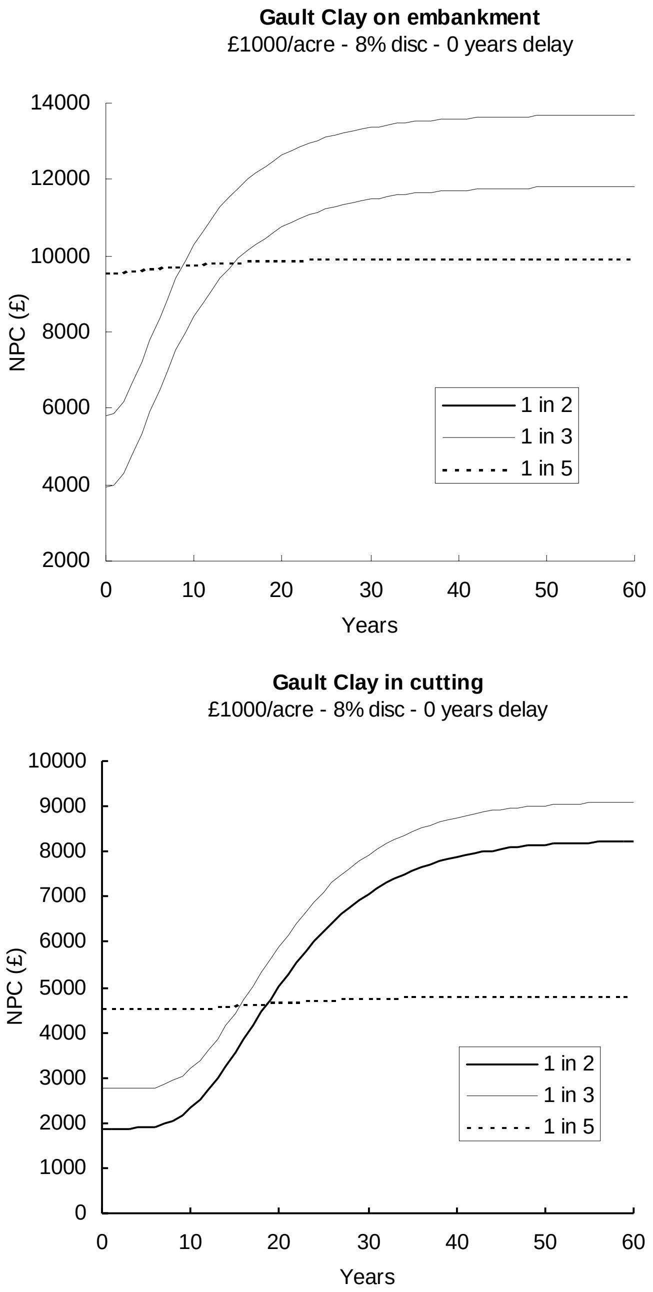


Figure 9 Graphs of Net Present Cost for Gault Clay

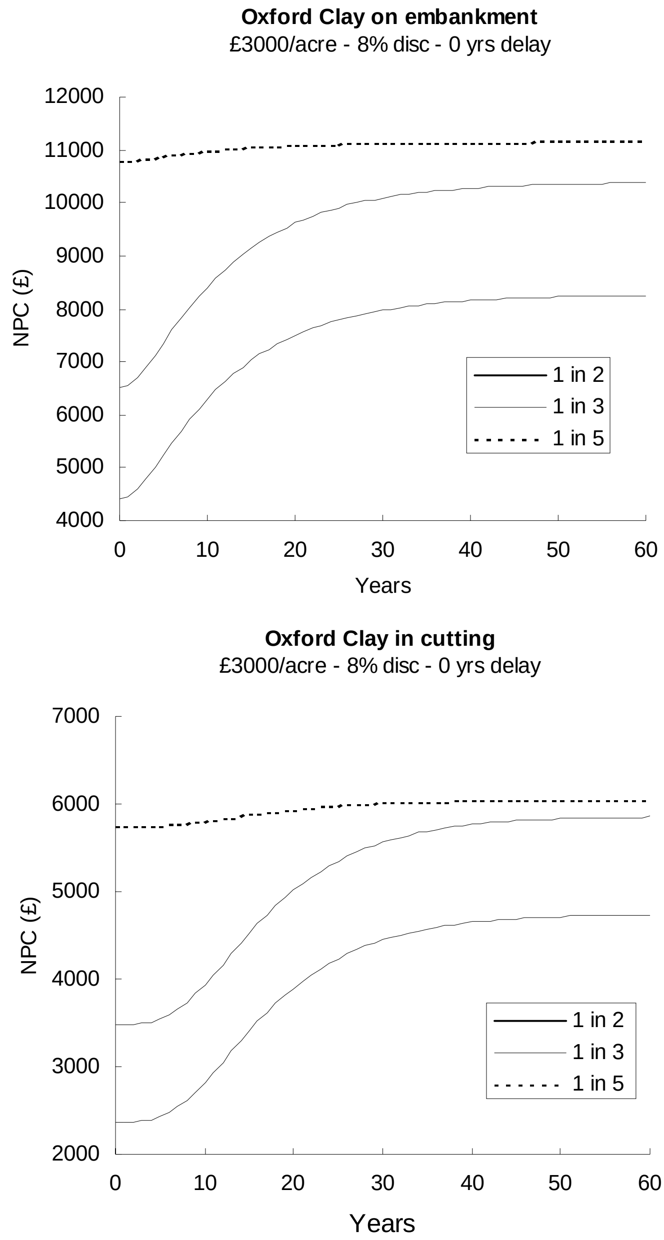
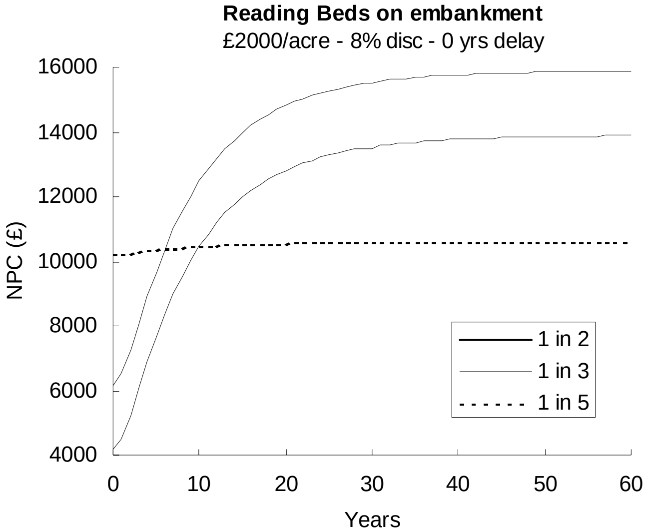


Figure 10 Graphs of Net Present Cost for Oxford Clay



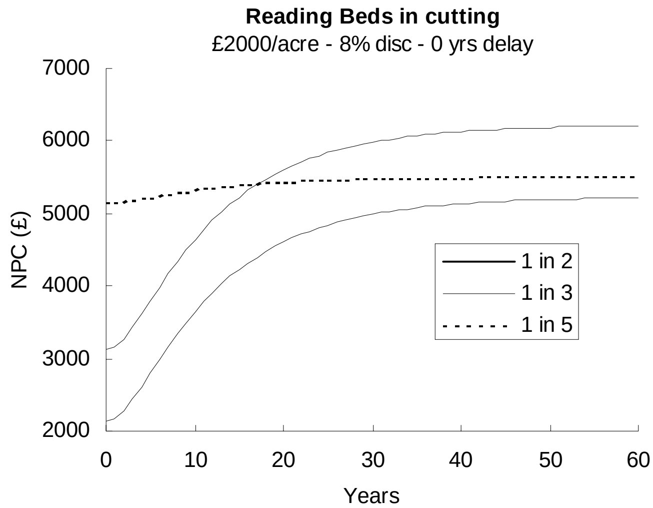


Figure 11 Graphs of Net Present Cost for Reading Beds

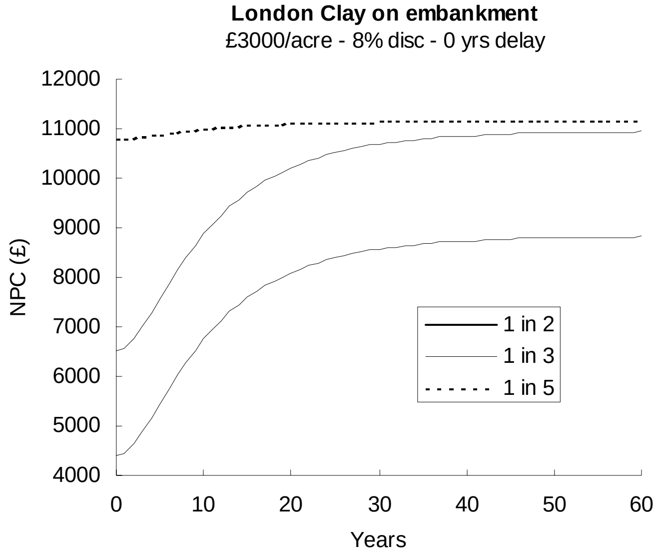


Figure 12 Graphs of Net Present Cost for London Clay

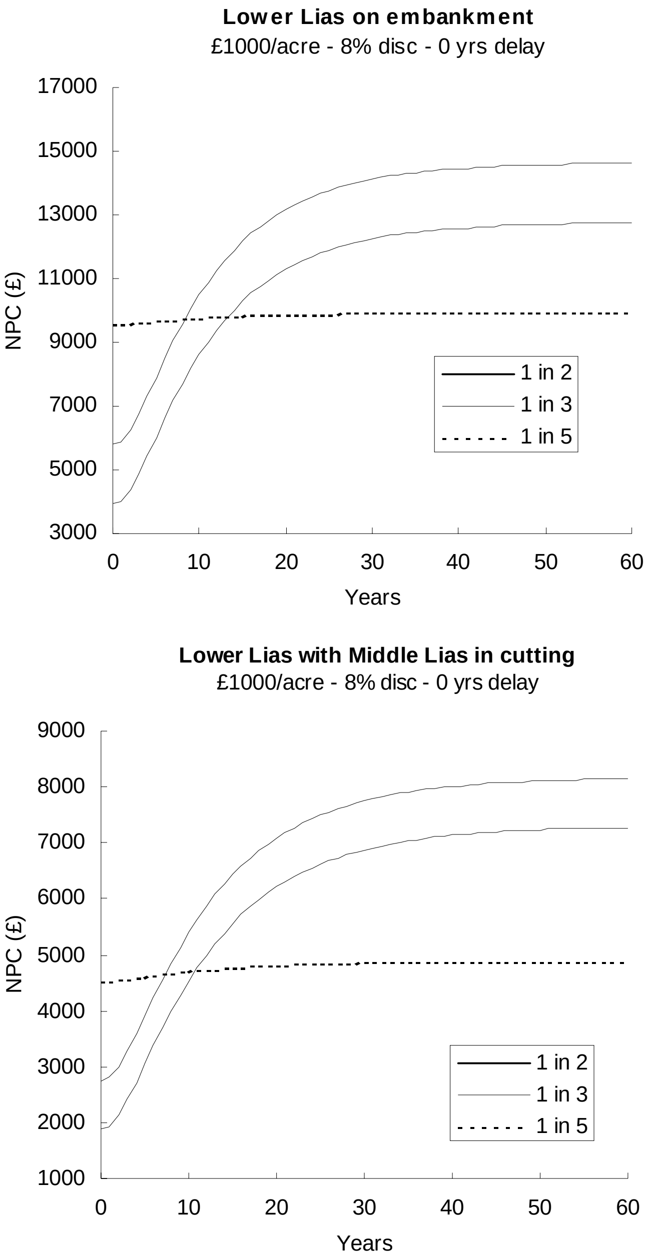


Figure 13 Graphs of Net Present Cost for Lower Lias

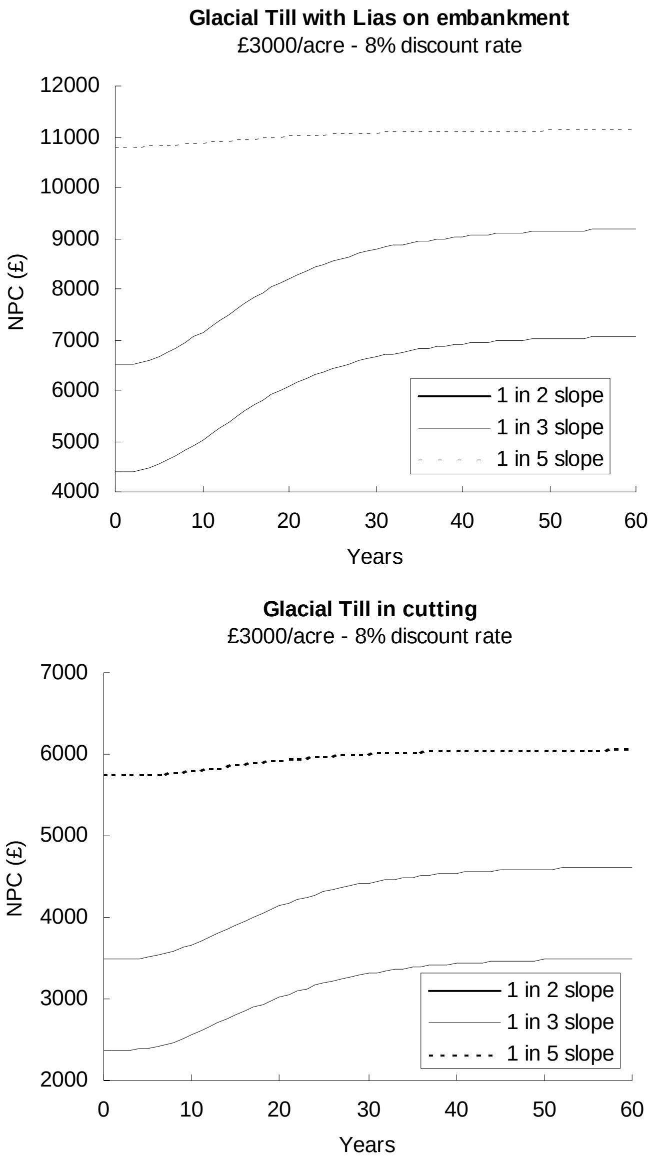


Figure 14 Graphs of Net Present Cost for Glacial Till

The tables and graphs are meant to allow a comparison of various engineering solutions on a whole life cost basis, and to assess the effect of varying parameters. They should not be regarded as accurate indications of the actual costs of construction and repairs for any section of earthworks. Following the convention of the US Federal Government (Ferry and Flanagan, 1991) analyses where the difference between two options is less then 10% are regarded as indeterminate.

6.1.2 Gault Clay

The Gault Clay is the material with the highest rates of slope failure in both cuttings and embankments, and hence is the material where the Net Present Costs are likely to show the greatest change from the capital costs. This is clearly shown on Table 3 and Figure 9. For the lowest land price of £1000 per acre, NPC_{30} is almost 3.0 times the capital cost for a 1:2 embankment and over 3.7 times the capital cost for a 1:2 cutting. Even at the highest land price used of £4000 per acre, NPC_{30} is 2.6 times the capital cost for a 1:2 embankment and 3.0 times the capital cost for a 1:2 cutting. Repair costs are clearly highly significant in whole life cost terms where there is a high failure rate. For a 1:5 slope, by contrast, with a much lower failure rate, NPC_{30} is only 1.03 times the capital cost for an embankment at the lowest land price, and 1.07 times the capital cost for a cutting.

The analyses show that, for Gault Clay, the NPC_{30} is always lowest for the 1:5 slope in both embankment and cutting. The 1:2 slope has the next lowest NPC_{30}, and the 1:3 slope always has the highest cost. This is despite the considerably higher capital costs for embankments and cuttings at 1:5. The 1:3 slope is always more expensive than the 1:2 slope, because the same failure rate is used for both. There are insufficient data to construct predictive equations for different slope angles, and observations by Perry (1989) and others indicate that the rate of failure does not vary greatly between slope angles of about 1:2 to 1:3; the greater instability of the steeper slopes is balanced by the greater penetration of rainwater and softening of the soil on the flatter slopes. The NPC curves for 1:3 slopes are thus parallel to those for 1:2 slopes, but displaced above them by the difference in capital cost.

Figure 9 illustrates how, despite the much higher capital cost of the 1:5 slopes, the cost of slope repairs results in this being the most economic option in the long term. For the lowest land price, the crossover in NPC values occurs at 9 years for a 1:3 embankment and 15 years for a 1:2 embankment. For cuttings, the crossover point occurs later than for embankments, due to the onset of slope instability being delayed for several years; at the lowest land price, the crossover occurs after 16 years for a 1:3 slope and 18 years for a 1:2 slope. As the land price rises, the crossover occurs at an increasingly later date; however, even at the highest land price, the 1:5 slope always gave the lowest NPC value after 30 years for both embankments and cuttings.

The NPC_{30} for the 1:5 embankment was more than 10% lower than that for the 1:2 embankment at land prices of £1000 per acre and £2000 per acre, but not at £3000 and £4000 per acre; the latter two analyses would therefore be regarded as indeterminate. For cuttings, however, the NPC_{30} for the 1:5 slope was more than 10% lower than that for the 1:2 slope at all land prices used in the analysis. The difference between the NPC_{30} for 1:5 slopes and 1:3 slopes was greater than 10% in all cases.

The 'residual' costs for 1:2 and 1:3 slopes (NPC_{60} - NPC_{30}) were generally of the order of £300 for embankments and £1200 for cuttings. This reflects the different predictive equations for cuttings and embankments; for embankments, the rate of failure was relatively low after 30 years, whereas for cuttings it was still significant (see Appendix A for graphs of % failure against time). These figures are discounted costs at present day prices for a length of 100 m over a period of 30 years, which gives an idea of the potential scale of future costs. The residual costs for 1:5 slopes were much lower, because of the lower failure rate. They did not exceed £100 in any of the cases analysed, and in most cases were less than £50. The values are shown as a percentage of NPC_{30} in Table 3. The values for 1:2 and 1:3 slopes range up to 16% for cuttings and 4% for embankments, and are less than 2% for all slopes at 1:5.

6.1.3 Oxford Clay

The rate of slope failures for Oxford Clay is lower than for Gault Clay, and as a result the 1:2 slope always has the lowest NPC_{30} value for both embankments and cuttings, followed by the 1:3 slope with the 1:5 slope always the most expensive (Table 4). The difference between 1:2 and 1:5 slopes is always greater than 10%, but that between 1:3 and 1:5 slopes is often less than 10%, particularly at low land prices. As can be seen on Figure 10, the graphs for 1:3 and 1:5 slopes tend to converge with time, whereas the graph for 1:2 slopes is always well below the other two.

Although the rate of failure is lower than for Gault Clay, it is still significant, as can be seen from the graphs on Figure 10 and by comparing the capital cost and NPC_{30} on Table 4. For a 1:2 embankment at the lowest land price, the NPC_{30} was 1.9 times the capital cost, and for a cutting it was 2.1 times the capital cost. This illustrates the importance of including slope repair costs in any economic analysis of potential earthwork solutions.

The residual costs were about 4% of NPC_{30} for embankments and 6% for cuttings for 1:2 and 1:3 slopes, and less than 2% for 1:5 slopes.

6.1.4 Reading Beds

For embankments, the 1:5 slope gives the lowest NPC_{30} for all land prices, and the difference between the 1:2 and 1:5 slopes is greater than 10% in all cases (Table 5). At the lowest land price of £1000 per acre, the NPC_{30} for a 1:2 embankment is 3.4 times the capital cost, compared with 1.04 times for a 1:5 embankment. The graphs of NPC against time rise steeply up to about 20 years and then flatten off (Figure 11). Residual costs are about 3% of NPC_{30} for 1:2 and 1:3 embankments, and less than 1% for a 1:5 embankment.

The pattern is different for cuttings. There, the 1:2 slope always gives the lowest NPC_{30}, though the difference between 1:2 and 1:5 slopes is only greater than 10% for the two highest land prices. The 1:3 slope always gives the highest NPC_{30}, though the difference between 1:3 and 1:5 slopes is greater than 10% only for the lowest land price. The NPC graph for 1:5 slopes converges with that for 1:2 slopes at the lowest land price, and rises with increasing land price to converge with the graph for 1:3 slopes at the highest land price. Residual costs are less than 3% of NPC_{30} for embankments and 6% for cuttings for 1:2 and 1:3 slopes and less than 2% for 1:5 slopes.

6.1.5 London Clay

Data for the rate of slope failure are only available for embankments of London Clay. The results of the NPC analyses are given on Table 6 and Figure 12. This is an important material in UK highways, as much of the M25 north of the Thames and the M4 in Berkshire are constructed on embankments of London Clay, and slope repairs are an ongoing cause of considerable expenditure in counties such as Essex and Hertfordshire.

The analyses reflect this maintenance expenditure; for 1:2 embankments, the NPC_{30} is 2.1 times the capital cost at the lowest land price, falling to 1.9 times at the highest land price. Despite these considerable maintenance costs, the 1:2 slope always gives the lowest NPC_{30}, and the difference between 1:2 slopes and 1:3 and 1:5 slopes is always greater than 10%. The capital costs for 1:3 and 1:5 slopes are significantly different, but the NPC graphs tend to converge with time and the NPC_{30} values are very similar. Residual costs are less than 3% of NPC_{30} for 1:2 and 1:3 slopes and less than 1% for 1:5 slopes.

6.1.6 Lower Lias

The figures for Table 7 and Figure 13 are based on a mixture of Middle and Lower Lias for cuttings and Lower Lias for embankments. They give an overall picture of the behaviour of overconsolidated clays of Liassic age, which are important over large stretches of the M5 and shorter stretches of other motorways.

The data for embankments and cuttings show that the 1:5 slopes always give the lowest NPC_{30}, despite much higher capital costs, and that the difference between 1:2 slopes and 1:3 and 1:5 slopes is always greater than 10%. The point at which the NPC value for 1:5 slopes becomes lower than that for 1:2 slopes increases from 11 years at the lowest land price to 18 years at the highest land price.

As with the other overconsolidated clays considered so far, the increase in NPC due to slope repairs is very significant (Figure 13); the ratio of NPC_{30} to capital cost for a 1:2 slope at the lowest land price is 3.1 for embankments and 3.6 for cuttings. The graphs of NPC against time rise steeply during the first 20 to 25 years then flatten out somewhat. Residual costs are less than 1% of NPC_{30} for embankments and about 6% for cuttings for 1:2 and 1:3 slopes and less than 1% for 1:5 slopes on embankments and in cuttings.

6.1.7 Glacial Till

The figures for Glacial Till (‘Boulder Clay’ in Perry (1989) and Andrews (1990)) are shown on Table 8 and Figure 14. The figures for embankments are based on a mixture of Glacial Till with Lower and Middle Lias clays. The rate of slope failure is lower for Glacial Till than for the other materials considered, and hence the NPC values are determined mainly by the capital costs. Thus 1:2 slopes give lower NPC values than 1:3 slopes, which in turn are lower than those for 1:5 slopes; this applies for both cuttings and embankments and at all land prices. The differences between the NPC_{30} values are greater than 10% for all the cases considered.

Slope repair costs still represent a considerable part of the NPC_{30} values. For embankments, the ratio of NPC_{30} to capital cost for 1:2 slopes ranged from 1.6 at the lowest land price to 1.5 at the highest land price. The equivalent ratios for 1:2 cuttings were 1.5 and 1.4, whereas for 1:5 slopes the ratios ranged from 1.07 to 1.03. The bulk of the increase in NPC has taken place by 30 years (Figure 14), leaving residual costs of around 6% of NPC_{30} for 1:2 and 1:3 slopes on embankment, 7% for the same slopes in cutting, and 2% for 1:5 slopes on embankment and cutting.

Table 9 Effect of varying discount rate on whole life cost analysis

Discount rate	*Slope type*	*Slope angle*	*Capital cost £k*	*NPC (30) £k*	*NPC (60) - NPC (30) / NPC (30) %*
6	Embankment	1 in 2	4.2	13.5	5.2
	Embankment	1 in 5	10.3	10.7	0.0
8	Embankment	1 in 2	4.2	11.8	2.5
	Embankment	1 in 5	10.3	10.6	0.0
10	Embankment	1 in 2	4.2	10.5	1.9
	Embankment	1 in 5	10.3	10.6	0.0
20	Embankment	1 in 2	4.2	7.3	0.0
	Embankment	1 in 5	10.3	10.4	0.0
30	Embankment	1 in 2	4.2	6.0	0.0
	Embankment	1 in 5	10.3	10.4	0.0

6.2 Discount rate

The standard discount rate of 8% was used in all the analyses in the preceding section. The effect of varying the discount rate, r, was investigated by carrying out a series of analyses on embankments of Gault Clay at 1:2 and 1:5 slopes. No delay period between failure and repair was incorporated, and the default average land price of £2180 per acre was used. The analyses were carried out for discount rates of 6, 8, 10, 20 and 30%. The results are shown on Table 9 and Figure 15.

Even small variations in discount rate have a dramatic effect on the NPC values for the 1:2 slope, where the rate of slope failure is significant. The NPC_{30} values decrease with increasing discount rate because this diminishes the effect of the maintenance costs. It must be stated again that the *actual* costs of construction and maintenance are the same, in present day costs, for all the analyses at the same slope angle shown on Figure 15

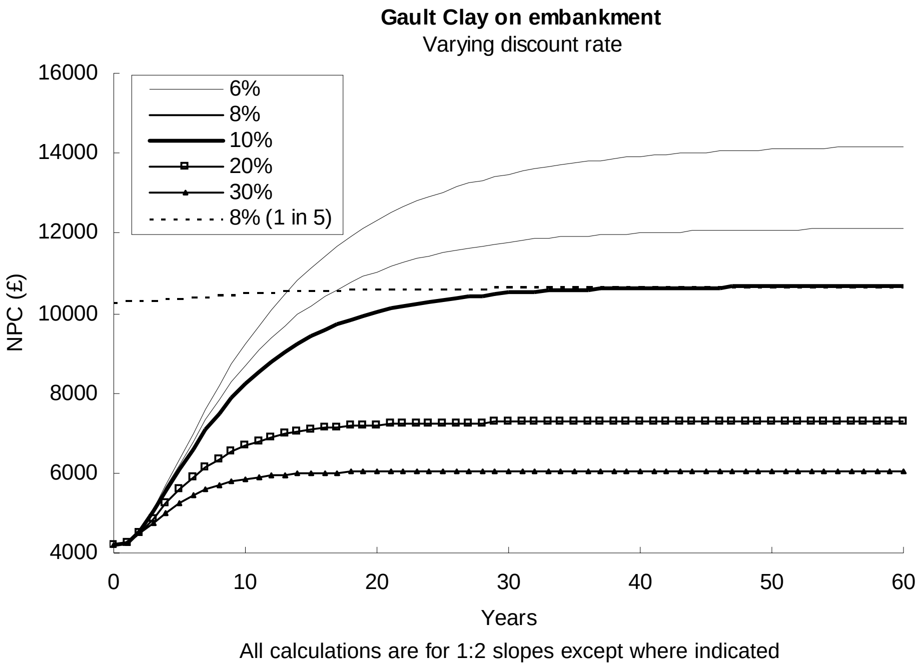


Figure 15 Net Present Cost analysis for Gault Clay at varying discount rates

and Table 9; the NPC value represents the cumulative *discounted* cost at any point in time. Thus the NPC_{30} value for the 1:2 slope decreases from £13.5k at a discount rate of 6% to £6.0k at 30%, although the actual cost is the same in both cases. The effect is much smaller for the 1:5 slope, for which repair costs are much lower. The NPC value represents the sum of money which must be invested at the start of the project to provide enough cash to carry out all the construction and maintenance activities which will be required over the period of the analysis at the given interest rate. The NPC values are not absolute costs, but a means of comparing different options on a whole life cost basis.

Varying the discount rate has an effect on the conclusions of the analysis. For the Gault Clay example, the 1:5 embankment has a significantly lower NPC_{30} value than the 1:2 embankment at discount rates of 6% and 8%. The values are almost identical at a discount rate of 10%, and for 20% and 30% the 1:2 embankment has significantly lower values of NPC_{30}. Increasing the discount rate will thus favour the option with the lowest capital cost, regardless of potential higher maintenance costs over the life of the structure.

6.3 Delay period

The analyses presented so far have been carried out assuming that slope failures and repairs are carried out in the same year. In practice there is often a delay between a failure being reported and the repair being carried out; the average delay in the slope repair database was found to be 2 years. A feature was therefore included in the programme to allow the repair to be delayed by up to 5 years. The effect of introducing a delay period was investigated for Gault Clay embankments at 1:2 and 1:5 slopes, using the standard discount rate of 8% and the average land price of £2180 per acre. The results are shown on Figure 16 and Table 10.

The effect of the delay period for the 1:2 slope is to push the graph to the right in the first 20 to 25 years. By 30 years, however, there is very little difference between the NPC values; the maximum delay of 5 years only reduces NPC_{30} by £0.3k from £11.8k to £11.5k, a mere 2.5%. For the 1:5 slope, there is no discernible effect on the NPC_{30} value. This suggests that in the long term delaying the repairs has no significant effect on the whole life cost; for the maximum delay period of 5 years, the 1:5 slope still has a lower NPC_{30} value than the 1:2 slope, though the difference is now less than 10%.

The delay period should be used with caution in the computer programme. In practice, if repairs are delayed, the size increases as the slip cuts back towards the crest of the slope. This results in higher repair costs than if they are treated as soon as possible. There is no information on the extent of the increase in costs, however, and this has not been incorporated into the model. In the computer

Table 10 Effect of delay period on whole life cost analysis

Delay period (years)	*Slope type*	*Slope angle*	*Capital cost £k*	*NPC (30) £k*	*NPC (60) - NPC (30) / NPC (30) %*
0	Embankment	1 in 2	4.2	11.8	2.5
	Embankment	1 in 5	10.3	10.6	0.0
1	Embankment	1 in 2	4.2	11.7	3.4
	Embankment	1 in 5	10.3	10.6	0.0
3	Embankment	1 in 2	4.2	11.6	4.3
	Embankment	1 in 5	10.3	10.6	0.0
5	Embankment	1 in 2	4.2	11.5	5.2
	Embankment	1 in 5	10.3	10.6	0.0

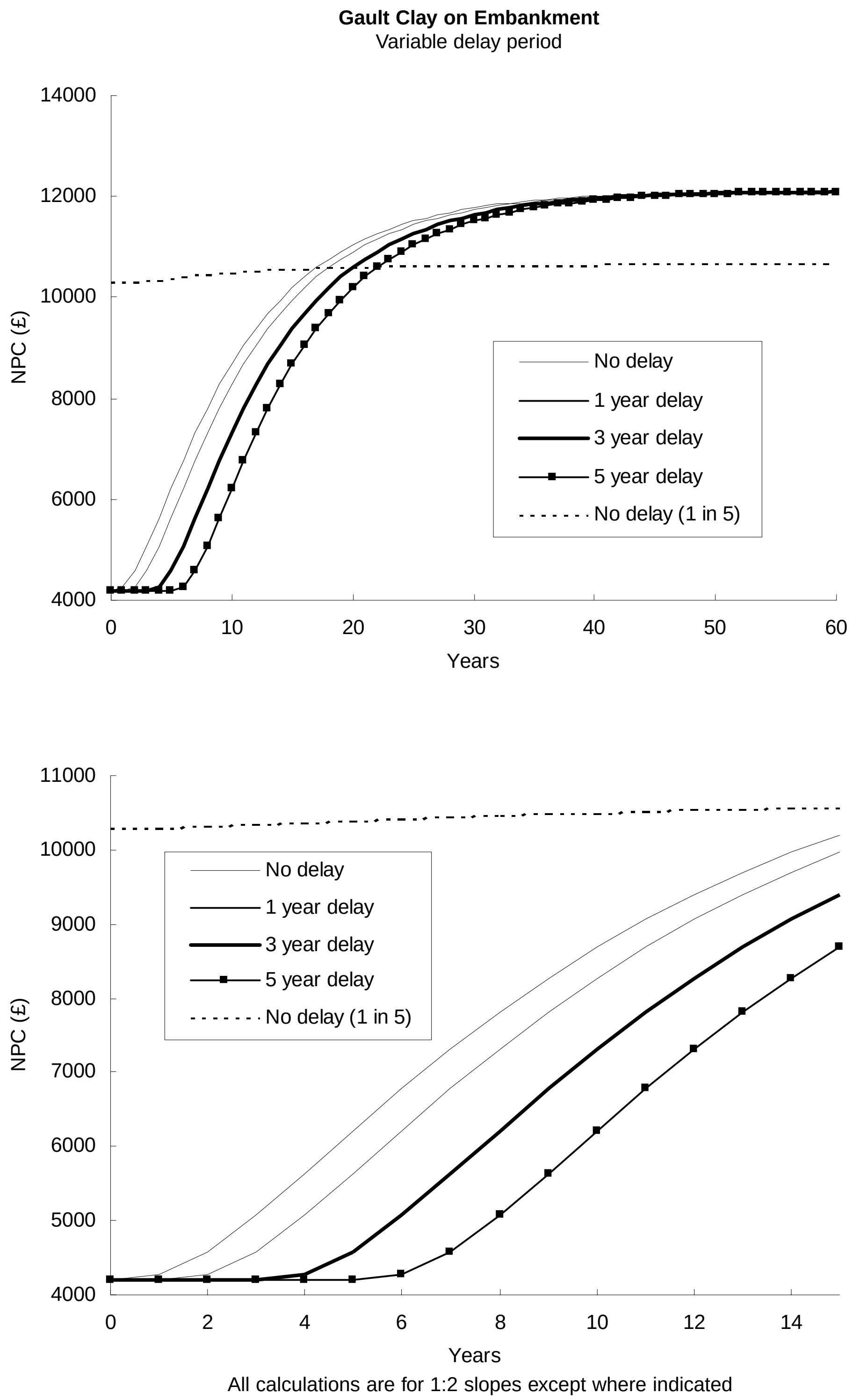


Figure 16 Net Present Cost analysis for Gault Clay at varying delay periods

programme, costs are simply deferred by a number of years selected by the operator, and are not increased to compensate for the increase in size of the repair. Use of this feature will thus result in an underestimate of the actual repair costs. This was a further reason for restricting the delay period to a maximum of 5 years, so that the errors would not become too large. It is recommended that this feature should not be used when comparing different options for earthworks design.

7 Further work

The programme provides a good method for estimating the whole life cost of various earthwork options for soils with a known high rate of minor slope instability. It is capable of further development, and would benefit from further background research in several areas.

The greatest limitation on the model is the prediction of soil failure rates. Data are limited to a relatively small number of soil types and to a maximum of 30 years since construction, and often much less. Data are available for most of the overconsolidated clays which are known to have significant amounts of minor slope instabilities. However, there are insufficient data to develop equations for different slope angles or earthwork heights. Only two equations have been developed for each soil type; an equation for slopes with high rates of failure, to cover all heights and all slope angles above a limiting value, and an equation for slope angles at or below the limiting value for which a rate of failure of less than 1% in 25 years was used, based on Perry (1989).

More detailed information on the rates of slope failure for a wider range of soil types, slope angles and heights and over a longer period would enable a greater range of equations to be developed and make the model more sensitive and versatile. However, such data are very hard to obtain. A further study of aerial photographs, to update the work of Andrews (1990), would provide useful data, especially in extending the time period for the equations. Even more useful would be comprehensive data sets for particular sections of road with slope instability problems, such as were available for the Cambridge Northern Bypass. However, it is rare for continuous records to be available.

If the prediction of slope failure rates can be improved, it would be worthwhile developing the model in various ways. These could include options to calculate construction costs using items from the Bill of Quantities for Highway Works (MCHW4) as well as CESMM, allowing for more complex earthwork geometries and a greater number of sections, including items such as topsoiling in the construction costs and grass cutting and litter collection in the maintenance costs, and improving the presentation and output options for the results of the analysis. However, it would be unwise to improve these features without an improvement in the basic data on failure rates.

8 Conclusions

1. Minor slope instabilities have occurred persistently on the motorway and trunk road network over the last 40 years. They are generally limited to higher stretches of embankments and cuttings in overconsolidated clays at slopes of 1:3 or steeper. The cost of repairing the failures is significant, especially in areas with a high proportion of overconsolidated clays.
2. The method of whole life costing allows an assessment to be made of construction and maintenance costs over the design life of an earthworks slope. A model was prepared using information on slope failure rates for a range of soil types and land acquisition costs, incorporating repair costs and construction costs. The model has been developed into a computer programme, WLCslope to allow the comparison of different options for earthworks design on a whole life cost basis. The programme produces graphs of Net Present Cost (NPC) against time and tabulates values of the capital cost, NPC at 30 years (NPC_{30}) and NPC at 60 years (NPC_{60}) for each earthwork. The user must specify the earthwork type, slope angle, length, height, soil type, failure rate, number of years for which the analysis is to be carried out, discount rate, land price, construction costs and repair costs. Default values are provided for discount rate, land price, construction costs, repair costs and failure rates for a range of soils.
3. A series of analyses was carried out for standard sections of cutting and embankment for a range of soil types, slope angles and land prices. The main conclusions were:
    - i For soils with a high rate of slope failures, the Net Present Cost values after 30 years (NPC_{30}) are often lower for slopes at 1:5, where the rate of failure is very low, than at 1:2 and 1:3, where the failure rate is much higher, despite the higher capital cost of the 1:5 slopes. Examples include Gault Clay and Reading Beds on embankment and Lower Lias and Gault Clay in cutting.
    - ii Even where the NPC_{30} values for 1:2 and 1:3 slopes are lower than for 1:5 slopes, repair costs constitute a major part of the whole life costs for steep slopes in overconsolidated clays. This may be illustrated by the ratio of NPC_{30} to capital cost. This ranges from 1.5 for Glacial Till up to 3.7 for Gault Clay. For flatter slopes with lower failure rates, the ratio does not exceed 1.07. This ratio would also apply to other materials with low rates of slope failure, such as sands and gravels.
    - iii The effect of increasing the land price is to reduce the relative contribution of slope repair costs to the whole life cost. Thus for Gault Clay on embankment, the NPC_{30} for a 1:5 slope is lower than that for a 1:2 slope at land prices of £1000 per acre and £2000 per acre, but higher at land prices of £3000 per acre and £4000 per acre. The land price is thus a significant factor in the whole life cost analysis.

- iv The residual cost of slope repairs after 30 years may be estimated by NPC_{60} - NPC_{30} expressed as a percentage of NPC_{30}. For the overconsolidated clays studied, this value was generally of the order of 5% to 10% for slopes at 1:2 and 1:3, but 2% or less for slopes at 1:5.

4 Varying the discount rate has a dramatic effect on the NPC values. The standard Treasury rate of 8% was used in the analyses quoted above, and is the default rate in the computer program. Increasing the discount rate favours options with a low capital cost - ie. steeper slopes - whereas decreasing it favours options with a low maintenance cost. Thus for an embankment on Gault Clay, a 1:5 slope gives a lower NPC_{30} than a 1:2 slope for discount rates of 6% and 8%, the values are almost identical at a discount rate of 10%, and the 1:2 slope gives lower values at discount rates of 20% and 30%.

5 The model assumes that slope failure and repair occur in the same year, but includes an option to delay the repair cost by up to 5 years. The average delay between failure and repair was found to be 2 years in a survey of 106 slope repairs. Introducing a delay period displaces the NPC/time graph to the right, but does not significantly affect the NPC_{30} value.

6 WLCslope provides a means of balancing construction and maintenance costs for earthworks slopes in discounted cash flow terms at present day prices. It can be used to choose between options for earthworks design in terms of whole life costs rather than purely on the basis of capital cost. It can also be used to compare the residual costs for different slope design options on DBFO schemes, where the responsibility for maintenance reverts to the Government after a period of typically 30 years. The model is relatively simple and should only be used for ranking different options, not for estimating actual costs.

7 The model is capable of further development and would benefit from further research into the rate of minor slope instabilities for a greater variety of soil types. More information on long term failure rates would be particularly valuable, as the data on which the model is based only extend up to 30 years from construction.

9 Acknowledgements

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Appendix A: Development of empirical relations between age of slope and frequency of failure

A1 Introduction

The aim of this stage of the model was to develop equations to describe the percentage of failures likely to occur in any given length of earthwork per year. This could then be multiplied by the average cost of a repair to obtain a cost profile for maintenance purposes. It was required that the amount of slope that fails over a given period of time may be predicted for a given soil type, slope type and slope angle.

A2 Data and methods

The data available to allow the development of the model included the slope failure database derived from a survey of the condition of slopes on motorways in England and Wales (Perry 1989). The database quantifies the influence of geology, geometry of slopes and the age of earthworks on the failure of slopes. The development of this database resulted in a report (Andrews 1990) relating age to the percentage failure of slopes. Age is defined as the time in years since the section of road was opened.

Additional information included comprehensive failure data for earthworks on the Cambridge Northern Bypass and a slope repair database (Perry and Reid, 1996) which gives details of a number of failures with no relation to the total length of earthworks. Although no percentage failures could be established from this data, it indicates the relation between number of failures and slope age.

The initial approach to analysing the slope survey data was to establish a general graphical relation between the age of slopes and the number of failures and then quantify that relation. Figure A1 shows the typical scatter of data for number of failures against age of road for all soil types based on the slope repair database of Perry and Reid (1996). The number of failures in the first 5 years is low, this is followed by a peak in the number of failures at about 12 years and then an exponential decay towards zero.

Analyses were carried out using SPSS statistical software and curves were fitted to the data. Linear,

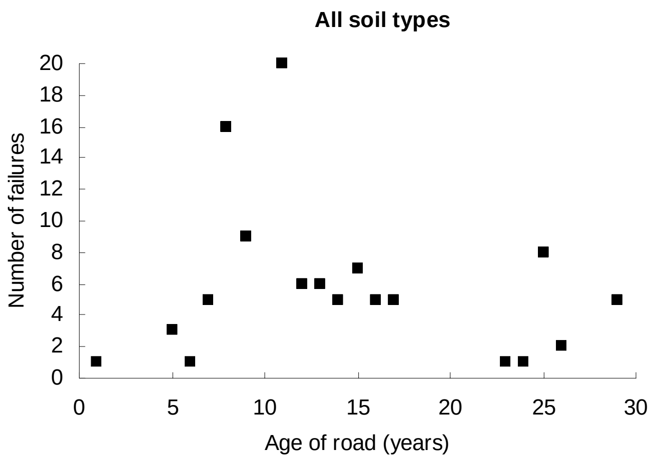


Figure A1 General scatter for data on al soil types

quadratic and cubic regression analyses were carried out and F values calculated to show the significance of the results. Non-linear regression was used to assess the applicability of the log-normal empirical expression.

A3 Percentage failure versus time

The results of the regression analyses were assessed for their statistical significance, bearing in mind the expected shape of a predictive failure / time curve over a period of up to 60 years and considering the limits within which the curves may be reasonably applicable. The curve should conform to the general shape shown on Figure 7 in the main report, though the exact shape at any location will depend on site specific factors such as soil type and slope angle.

The statistical significance of the regressions were assessed by means of the R^2 value and the F-test results. The significance of the R^2 and F values can be obtained from standard statistical tables (Lindley and Miller 1952) for the total number of degrees of freedom due to the regression and the number of data points respectively. R^2 is a ratio of the sum of squares due to regression SS_R, which provides a measure of the variation of the regression line around the mean, to the total sum of squares SS_T. The nearer this value is to unity the more the estimated and actual values of the dependent variable (percentage failures) correspond and the *better the fit*.

A3.1 Simple regression

Linear regression is not the most appropriate tool for obtaining a realistic curve but has been used to assess the increased significance as the regression model is changed from linear to quadratic, to cubic and then to log-normal non-linear regression. Linear equations indicate a gradual decrease in the number of failures per year with increasing time. They overestimate the number of failures in the first five years and underestimate the peak values.

Quadratic regression output indicates that for the data on all soil types the quadratic curve is a highly significant fit. However, if this curve were to be used to predict the future number of slope failures beyond 30 years it would suggest there were none, or a negative number. This is unrealistic as failures are expected to continue to occur beyond the slope age of 30 years.

Cubic regression on the data for all soil types shows a highly significant fit when the F-test is applied. However, the shape of the curve suggests that after about 25 years the number of failures will start to increase rapidly. This is inappropriate as, from experience, the number of failures is likely to reduce slowly after about 25 years.

A3.2 Non-linear regression

A non-linear, log-normal regression was carried out in an attempt to obtain a significant fit to the Cambridge Northern Bypass data as well as the data for all soil types. A log-normal distribution was used as it fits the expected shape fairly well with a peak followed by an exponential decay as shown in Figure A2.

Best fit curves were obtained by maximising R^2. Figure A2 shows the best fit log-normal curve to the Cambridge Northern Bypass data. Figure A3 shows the best fit log-normal curve to the data for all soil types. This curve indicates zero failures after 25 years which is inconsistent with the data. Figure A4 shows a curve which corresponds better to the expected shape. This curve is a result of the manipulation of the three constants A, B and C in order to achieve a peak at about 10 years (C=9.8) followed by a gradual reduction in the number of failures towards zero. The rate of the reduction in number of failures after the peak is determined by the constant B. By fixing the constants B and C in order to achieve the required peak position and exponential decay rate, the equation was entered into SPSS with only one variable, A, to be determined. The value of A corresponds to the peak number of failures. SPSS gave the best fit curve shown in Figure A4 for values of B and C fixed at 1.5 and 9.8 respectively, giving a value of A of 9.6. This A value slightly underestimates the peak in the number of failures but generally better represents the expected shape of the curve. From the SPSS output, the best fit log-normal curve is that shown in Figure A3, any alteration of the constants from the values used to plot this curve will naturally produce a curve with a lower R^2 value.

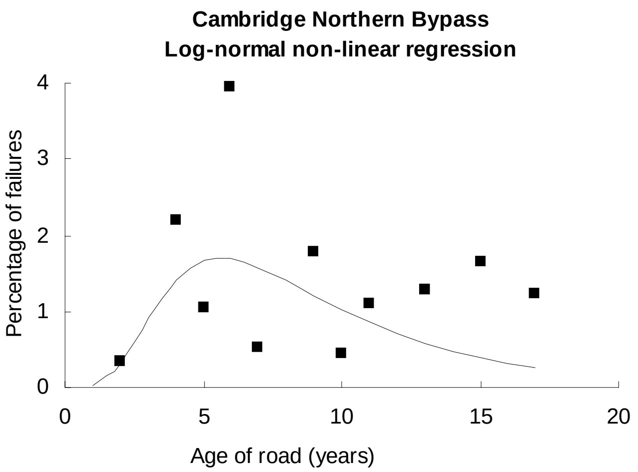


Figure A2 Log-normal regression on CNB data

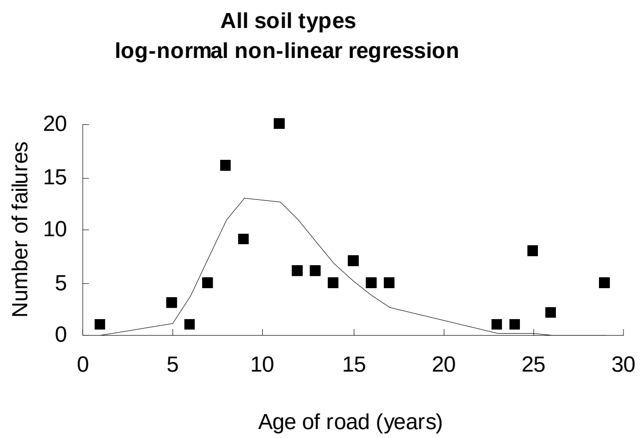


Figure A3 Log-normal regression on data for all soil types

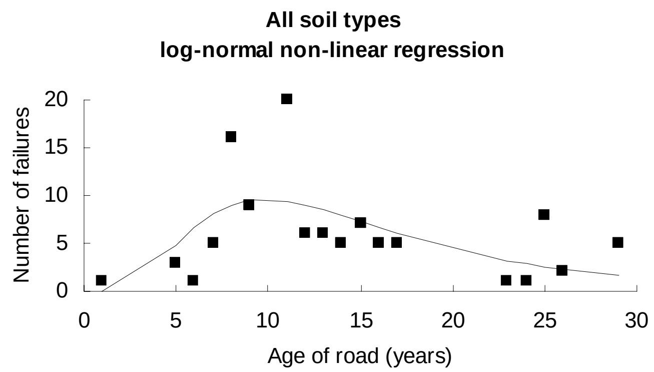


Figure A4 Adjusted log-normal regression on data for all soil types

A4 Cumulative failures versus time

A quantifiable relationship between number of failures and the age of the earthwork is more easily achieved by analysing plots of the cumulative number, or percentage, of failures against age.

Table A1 shows the results of some of the regression analyses for cummulative frequency. The rows labelled

Table A1 Summary of cumulative distribution results

Cambridge Northern Bypass

	Quadratic model $Y=A+Bx+Cx^2$	*Cubic model* $Y=A+Bx+Cx^2+Dx^3$	*Log-normal model* $Y=Ae^{-B(ln(x/c))^2}$
Figure	A5	A7	A9
A	-2.7863	-2.7241	15.5360
A-lower	-	-	12.2799
A-upper	-	-	18.7922
B	1.6662	1.6298	0.5396
B-lower	-	-	0.2148
B-upper	-	-	0.8644
C	-0.3620	-0.0313	23.3582
C-lower	-	-	11.2576
C-upper	-	-	35.4587
D	-	-0.0002	-
R^2	0.976	0.976	0.980
F	279.33	172.99	-
Sig.F	>99.999%	>99.999%	-

All soil types

	Quadratic model $Y=A+Bx+Cx^2$	*Cubic model* $Y=A+Bx+Cx^2+Dx^3$	*Log-normal model* $Y=Ae^{-B(ln(x/c))^2}$
Figure	A6	A8	A10
A	-28.890	-16.164	99.666
A-lower	-	-	95.068
A-upper	-	-	104.263
B	8.9616	4.4293	1.125
B-lower	-	-	0.793
B-upper	-	-	1.458
C	-0.1517	0.2296	23.977
C-lower	-	-	21.366
C-upper	-	-	26.588
D	-	-0.0087	-
R^2	0.936	0.948	0.981
F	109.98	85.20	-
Sig.F	>99.999%	>99.999%	-

'lower' and 'upper' show values for the asymptotic 95% confidence intervals. These are 'large sample' approximations for the confidence intervals for each of the parameters A, B and C (equation 1). SPSS is unable to obtain exact confidence intervals.

The row labelled 'Sig.F' gives an indication of the level of significance of the curve fit defined by percentage points of the F-distribution. A Sig.F value of 95% indicates that the calculated value of F exceeds the value tabulated (Lindley and Miller, 1952) for the 5% points of the F-distribution for the particular number of degrees of freedom. The hypothesis being tested by the SPSS software is that $R^2 = 0$, i.e. there is no correlation between the variables, thus a significant F value of 95% rejects this hypothesis at the 95% (confidence) level. Figures A5 to A8 show the results of the quadratic and cubic regression analyses.

A4.1 Non-linear regression

Figure A9 shows the cummulative log-normal equation best fit for the data on the Cambridge Northern Bypass. Within the limits of the data the curve describes the relation very well. R^2 is equal to 0.9795 which is slightly higher than its value for the cubic fit. Figure A10 shows the log-normal best fit curve to the data for all soil types. This equation describes the behaviour of the earthworks in

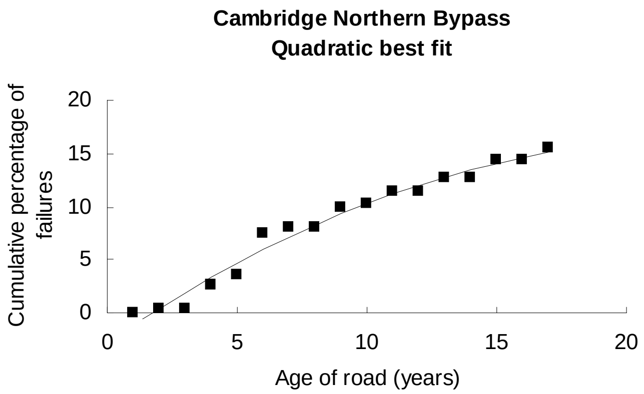


Figure A5 Quadratic regression on cumulative CNB data

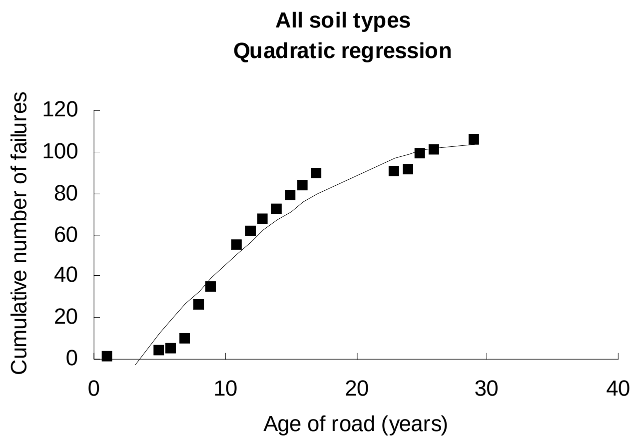


Figure A6 Quadratic regression on-cumulative data for all soil types

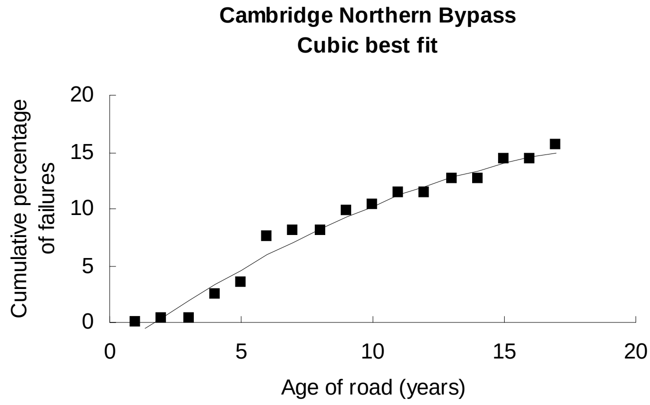


Figure A7 Cubic regression on cumulative CNB data

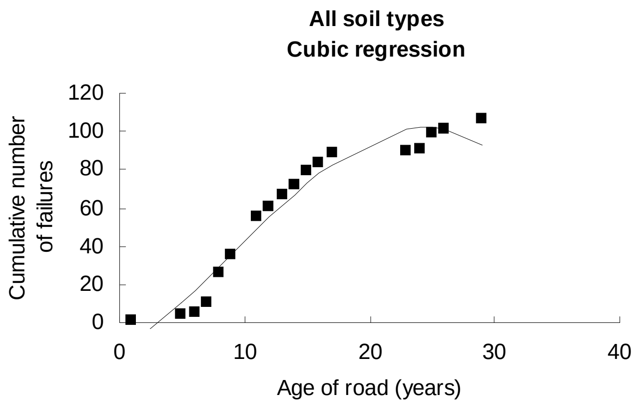


Figure A8 Cubic regression on cumulative data for all soil types

the first 23 years very well. R^2 is increased from the cubic best fit and is equal to 0.981. However, after 23 years the curve predicts a fall in the cumulative number of failures which is unrealistic.

Table A1 shows highly significant curve fits for quadratic, cubic and log-normal regression. Ideally, the simplest form of the equation should be used but this may not be appropriate due to the inability of the quadratic curve to accurately predict the failure rate in the first few years.

The problem with the log-normal distribution is that with time the curves show a reduction in the cumulative number of failures. The ideal distribution shows a cumulative curve tending to a constant maximum value, this is the integrated log-normal expression shown in Figure A11.

A5 Discussion

A5.1 The integrated log-normal model

The integrated log-normal expression appears to best describe the relation between percentage failures of earthwork slopes and the age of the slope, equation (1).

(1)

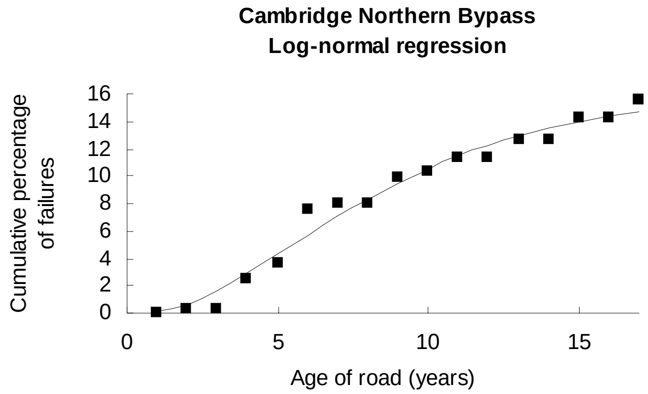


Figure A9 Log-normal regression on cumulative CNB data

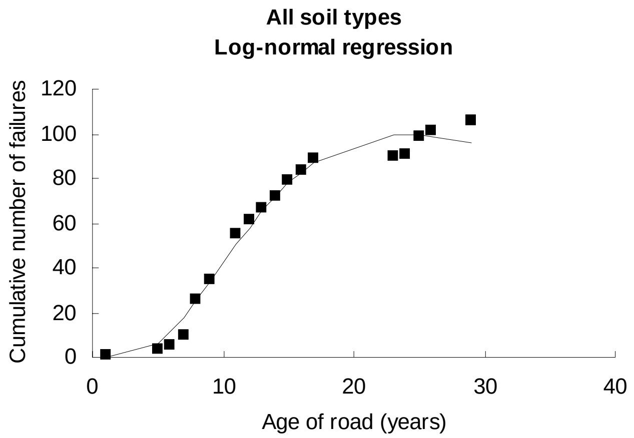


Figure A10 Log-normal regression on cumulative data for all soil types

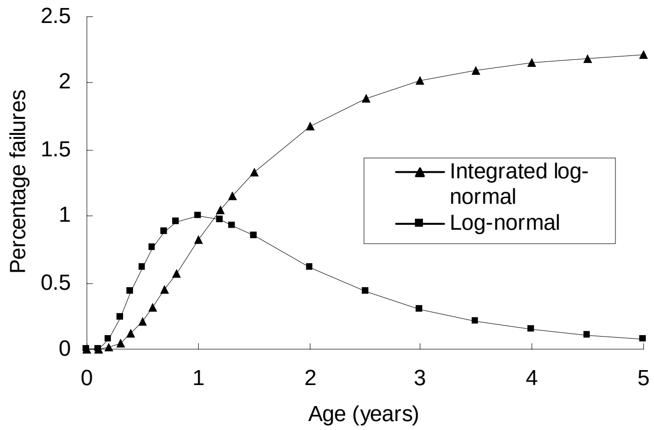


Figure A11 Plots of the log-normal and integrated log-normal distributions with constants A=B=C=1

Where Y is the cumulative percentage failures of the slope, x is the age of the slope and A, B and C are constants.

The equation is derived by integrating the frequency distribution f against time t, which is a form of the log-normal expression used in previous sections, equation (2).

(2)

Where A is the maximum value of the frequency (percentage failures) which occurs at time t=C. The constant B is a parameter which determines the spread of the distribution, f(0)=0 and f(∞)=0.

erf( ) is the error function defined by equation (3):

(3)

Figure A11 shows plots of f(t) and Y with A=B=C=1 to show the general form of the distribution which would describe few initial slope failures followed by a peak in the number of failures with a slow tailing off to zero.

The shape of the curve is defined separately for each soil type by manipulating parameters A, B and C. A corresponds to the peak value of the log-normal distribution and C is the age at which this occurs. B defines the shape of the curve. Where possible, A and C are selected from the graphs of percentage failures against time given in Andrews (1990) and B is adjusted to give the visual *best fit* to the cumulative data. The actual data points and the curves produced by the predictive equations are shown in Figures A12 to A26. Although no statistical significance can be established for the reliability of the curve fits, a knowledge of slope behaviour and analysis of the data have led to the adoption of the cumulative distribution as the most reliable predictor for likely slope failure rates.

A5.2 Application of the model

A summary of all the analyses is shown in Table A2. The parameters A, B and C are shown along with the corresponding length of earthwork which was covered in the original survey for each soil type. The column labelled Y(60) shows the predicted percentage of slope failed after 60 years and Y(¥), the ultimate percentage failed.

The information in Table A2 has been used as a basis for the development of the computer model for the whole life cost of earthworks. Figures A12 to A26 show the graphs associated with the soil types listed in Table A2.

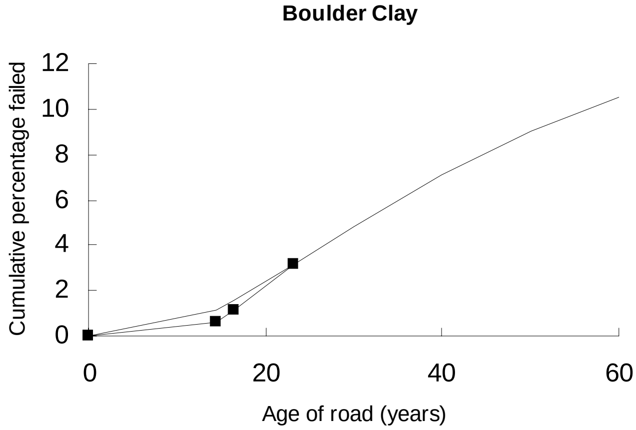


Figure A12 Boulder Clay slope failures in cutting

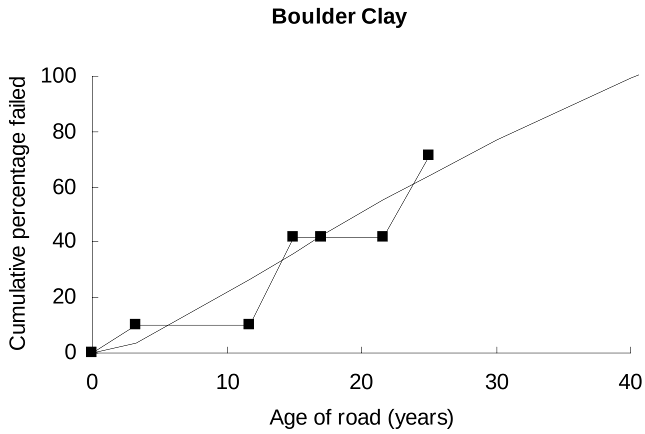


Figure A13 Boulder Clay with Glacial Gravel and Middle Lias on embankment

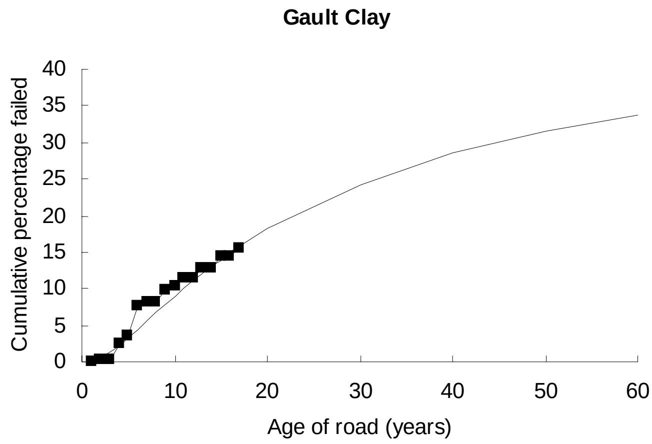


Figure A16 Gault Clay on embankment

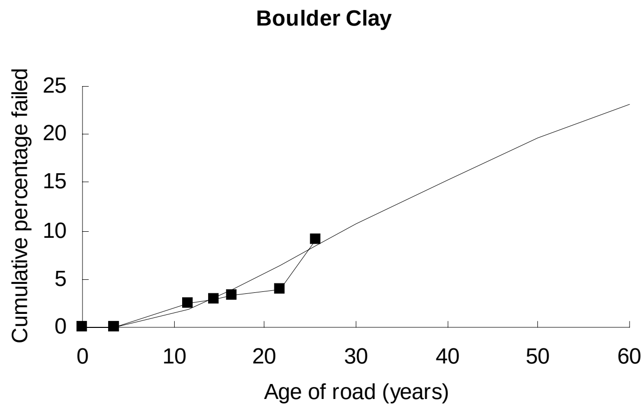


Figure A14 Boulder Clay with Lower Lias and Middle Lias on embankment

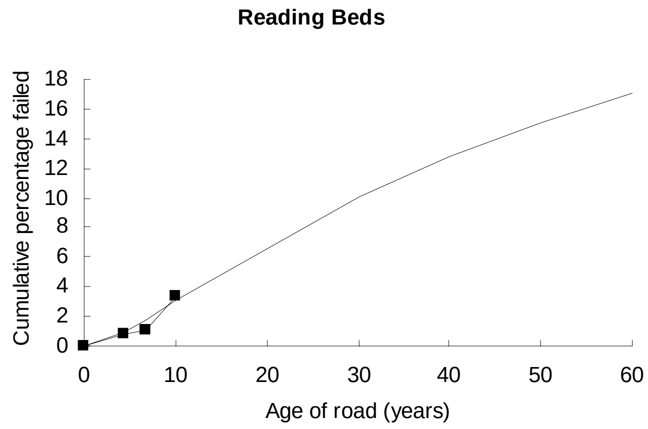


Figure A17 Reading Beds in cutting

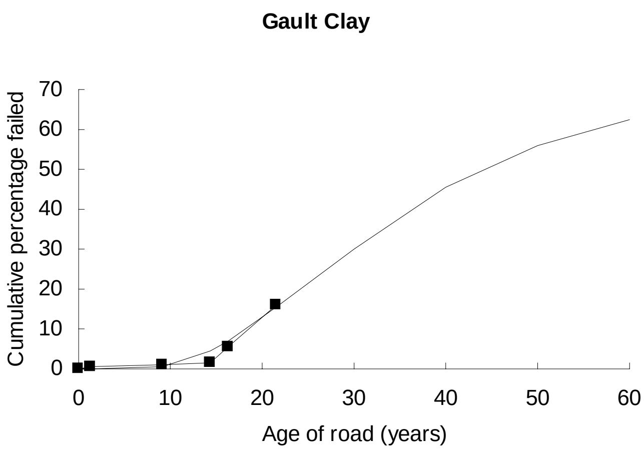


Figure A15 Gault Clay in cutting

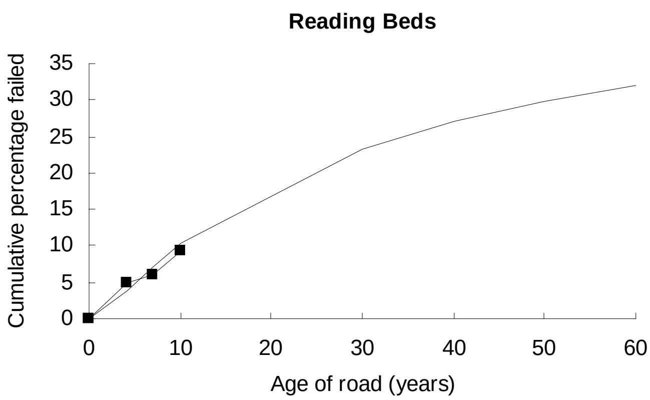


Figure A18 Reading Beds with London Clay on embankment

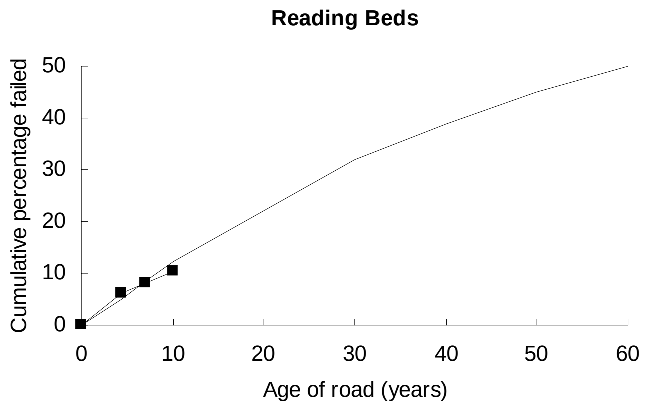


Figure A19 Reading Beds on embankment

Figure A20 Oxford Clay in cutting

Figure A21 Oxford Clay on embankment

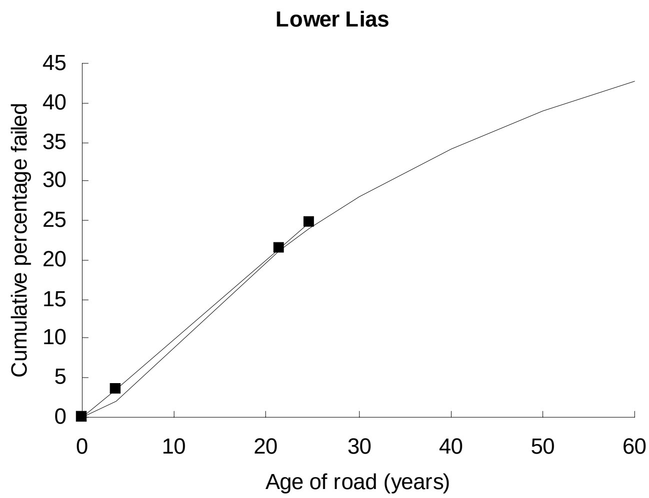


Figure A22 Lower Lias on embankment

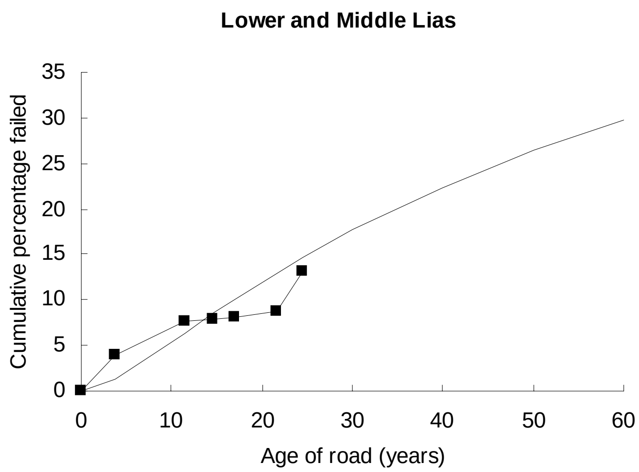


Figure A23 Lower Lias and Middle Lias in cutting

Figure A24 London Clay on embankment

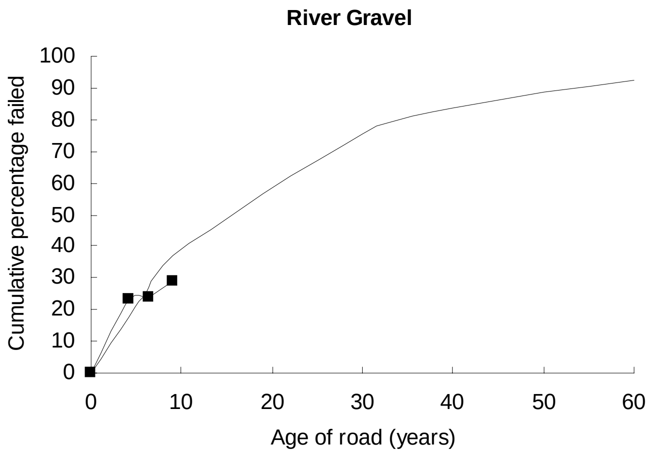


Figure A25 River Gravel with Reading Beds on embankment

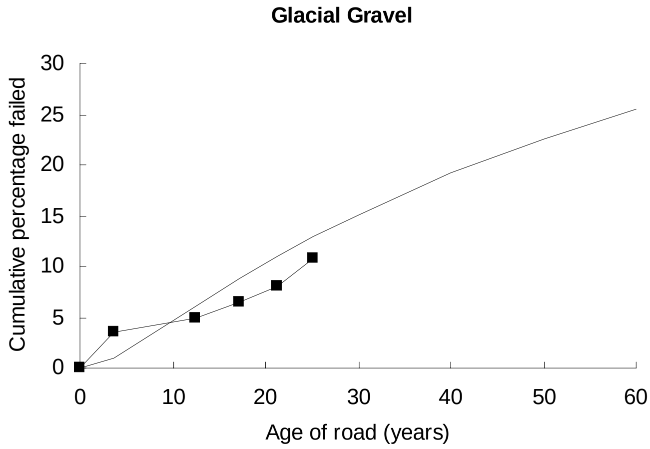


Figure A26 Glacial Gravel with Middle Lias on embankment

Table A2 Summary data for all soil types

Nº	*A*	*B*	*C*	*Figure*	**Length (m)*	***Slope (min)*	****Nº data points*	*Y(60) %*	*Y(¥) %*	*Notes*
Boulder Clay										
1	0.25	1.1	25	A12	2775	1 in 2	3	10.5	16.5	Cutting
2	0.5	1.4	25	A14	3404	1 in 2.5	6	23.2	50.6	Embankment, with Lower Lias and Middle Lias
3	3	2	12	A13	1270	1 in 3	6	100	100	Embankment, with Glacial Gravel and Middle Lias
Gault Clay										
4	1.8	0.8	25	A15	3695	1 in 3.5	5	62.7	74.9	Cutting
5	1.15	1.6	7.0	A16	19000	1 in 2	17	33.8	43.3	Embankment
Reading Beds										
6	0.4	2.0	10	A17	20255	1 in 3.5	3	17.0	38.5	Cutting
7	1.2	2.0	4.0	A18	6830	1 in 3.5	3	32.0	46.3	Embankment, with London Clay
8	1.4	2.0	4.0	A19	39995	1 in 3.5	3	37.3	54.0	Embankment
Oxford Clay										
9	0.5	1.0	20	A20	5300	1 in 2.5	6	18.3	22.8	Cutting
10	0.5	2.0	10	A21	12125	1 in 2.5	6	21.3	48.2	Embankment
Lower Lias										
11	1.2	1.8	8	A22	5995	1 in 3.5	3	42.8	68.9	Embankment
12	0.7	2.0	10	A23	7510	1 in 3	6	29.8	67.5	Cutting, with Middle Lias
London Clay										
13	0.6	1.8	8.0	A24	55140	1 in 2.5	3	21.4	34.4	Embankment, no data available for cuttings
River Gravel										
14	5.0	1.8	3.0	A25	440	1 in 2	3	92.5	100	Embankment, with Reading Beds, no data available for cuttings
Glacial Gravel										
15	0.6	2.0	10	A26	2050	1 in 2.5	5	25.5	57.8	Embankment, with Middle Lias, no data available for cuttings

** The 'length' column shows the length of slope covered in the survey, the sample size, giving an indication of the reliability of the predictive curve*
*** The 'slope' column shows the shallowest slope angle at which failures were recorded*
**** The nº of data points used in plotting the graphs: the more points, the more reliable the predictive curve*

A6 References

Andrews R D (1990). *Determining the age of failure of motorway earthworks from aerial survey photographs*. Research Report RR257. Transport Research Laboratory, Crowthorne.

Perry J (1989). *A survey of slope condition on motorway earthworks in England and Wales*. Research Report RR199. Transport Research Laboratory, Crowthorne.

Perry J and Reid J M (1996). *Whole life cost model for earthwork slopes: status report*. Project Report PR/CE/202/96. Transport Research Laboratory, Crowthorne. (*Unpublished report available on direct personal application only*)

Lindley D V and Miller J C P (1952). *Cambridge elementary statistical tables*. Cambridge University Press.

Appendix B: Example calculation of whole life costs

Objective

To work through an analysis with certain fixed and variable parameters to illustrate each step of the program.

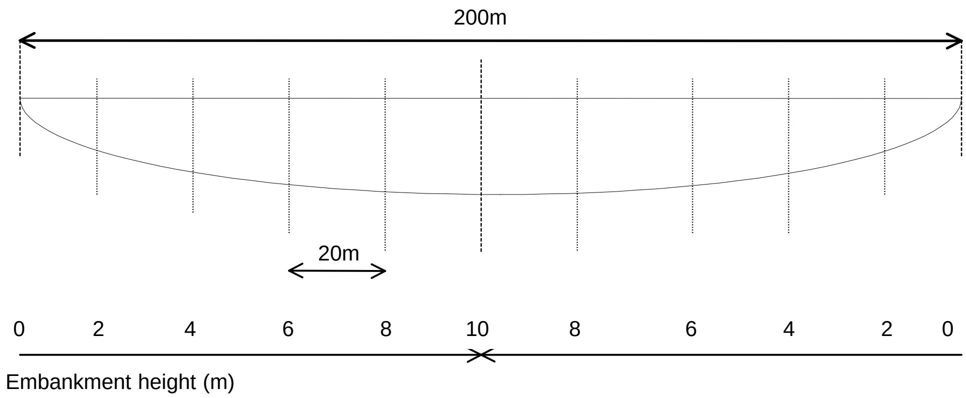
Fixed parameters

- Soil type - Gault Clay
- Slope type - embankment
- Cost period - 30 years
- Delay period - 2 years
- Cost items - as default values
- Length/height - see figure below

Variable parameter

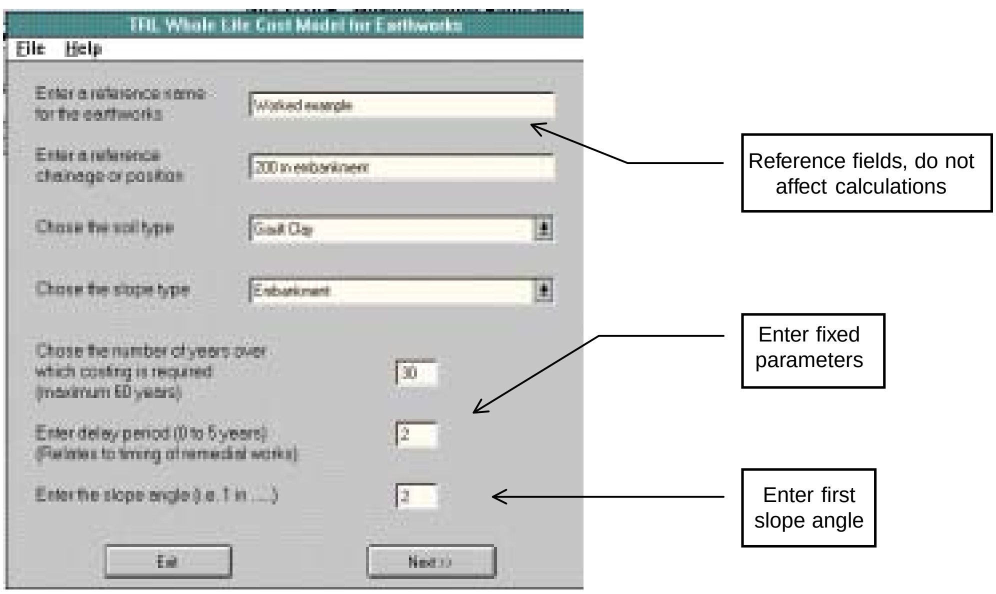
- Slope angle - vary between 1 in 2 and 1 in 5

Slope geometry (plan view)

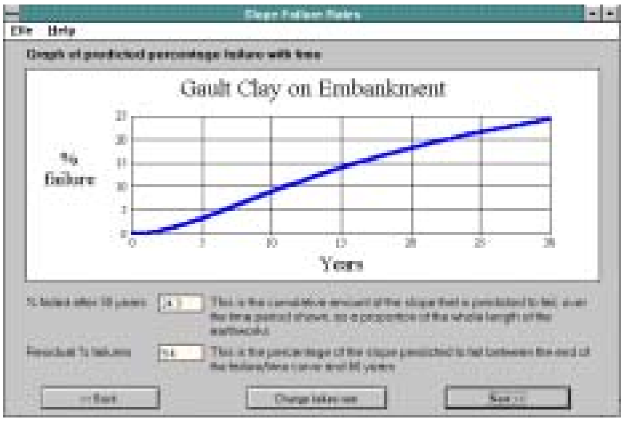


Quick calculation route

Stage 1 - User Input



Stage 2 - Failure rates displayed



Failure rates are displayed. For the purpose of this worked example, these failure rates are accepted.

Stage 3 - Summary

'Next' is chosen for the quick calculation method

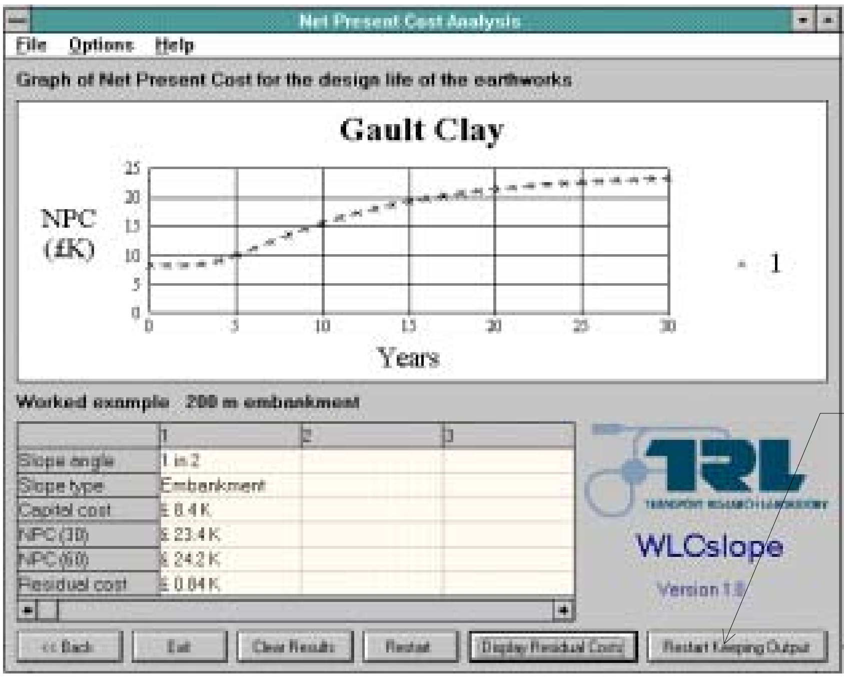
Stage 4 - Cost calculation

Default cost values are displayed by clicking on 'Display Defaults' from the | File | menu

Slope geometry is entered

Capital cost is displayed by clicking on 'OK'

Stage 5 - Whole life cost analysis

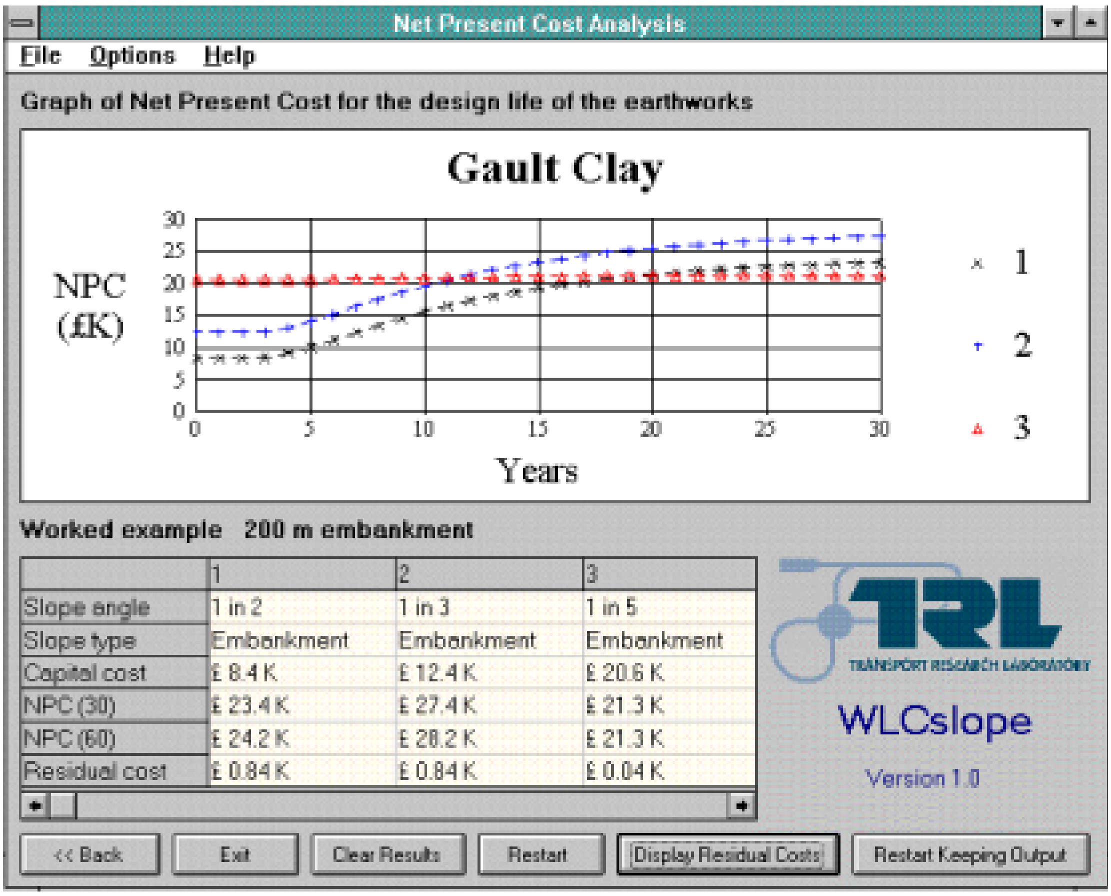


Results of first analysis (1 in 2 slope) are displayed graphically and in the table

This button is chosen to restart the program for the next analysis

The program will now return to stage 1 where the slope angle is changed to 1 in 3. No alterations are made at stages 2 to 4 so that comparison can be made between the whole life costs of the earthwork with varying slope angle. After the analysis of the 1 in 3 slope, the process is repeated for a 1 in 5 slope. The final output after the three analyses is shown below

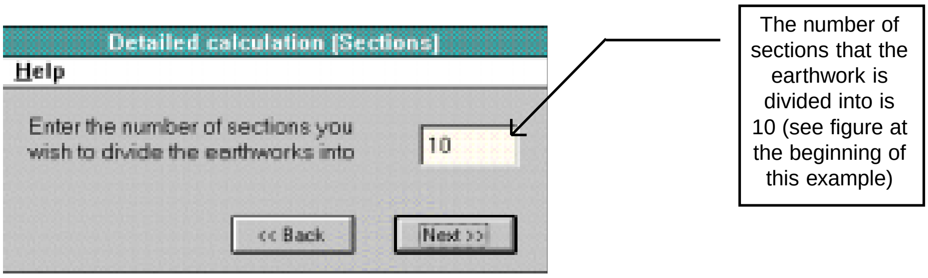
Final output



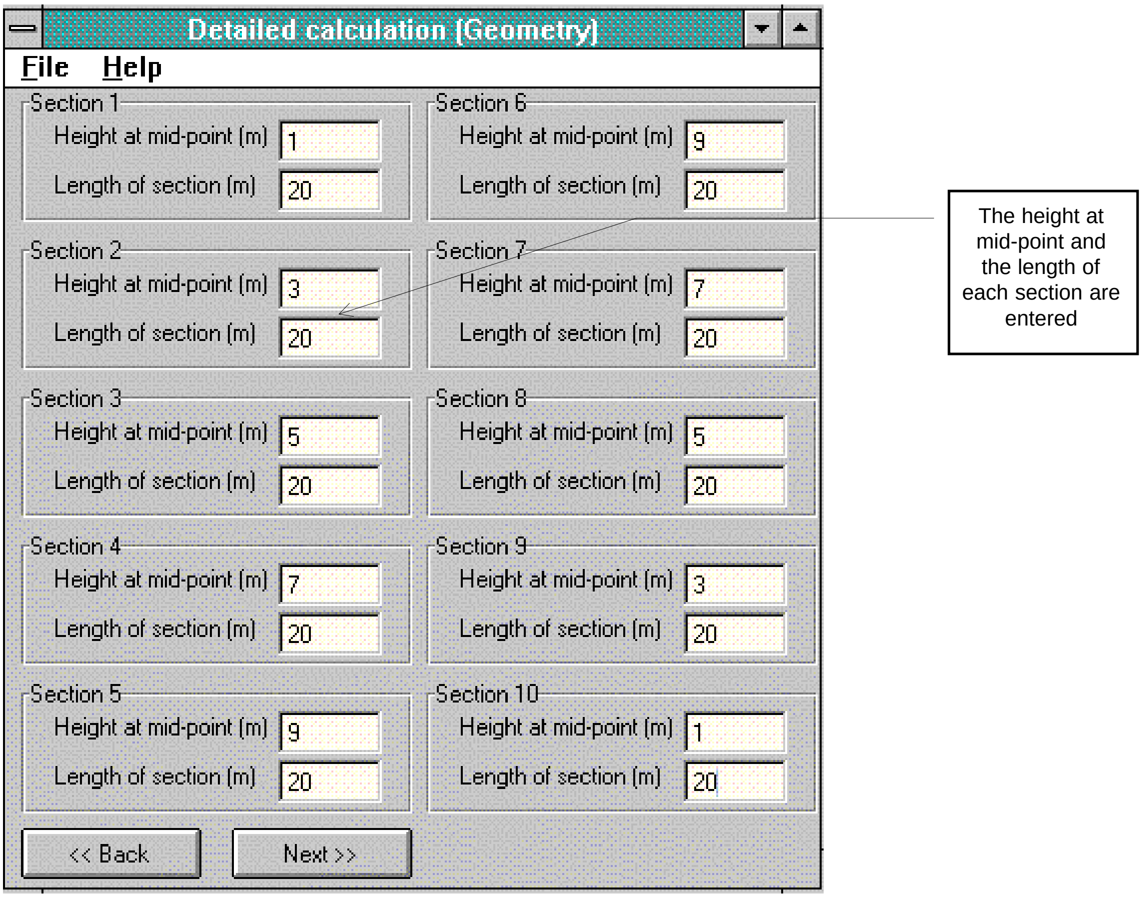
Detailed calculation route

Stages 1 to 3 are the same as those for the quick calculation route except at stage 3, the detail_calc button is chosen.

Stage 4 - Sections

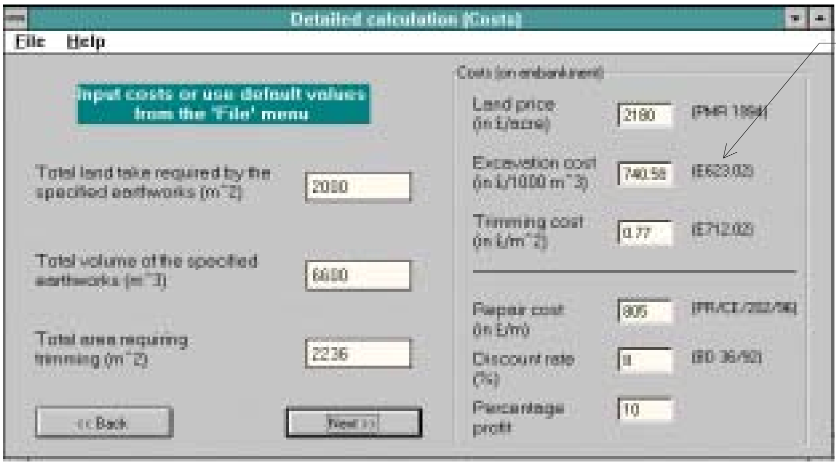


Stage 5 - Geometry



At this stage, the inputs are saved as a *.geo file (choose 'Save Geometry' from the |File| menu). This file can be recalled when repeating the analysis for different slope angles so the geometry does not have to be entered each time.

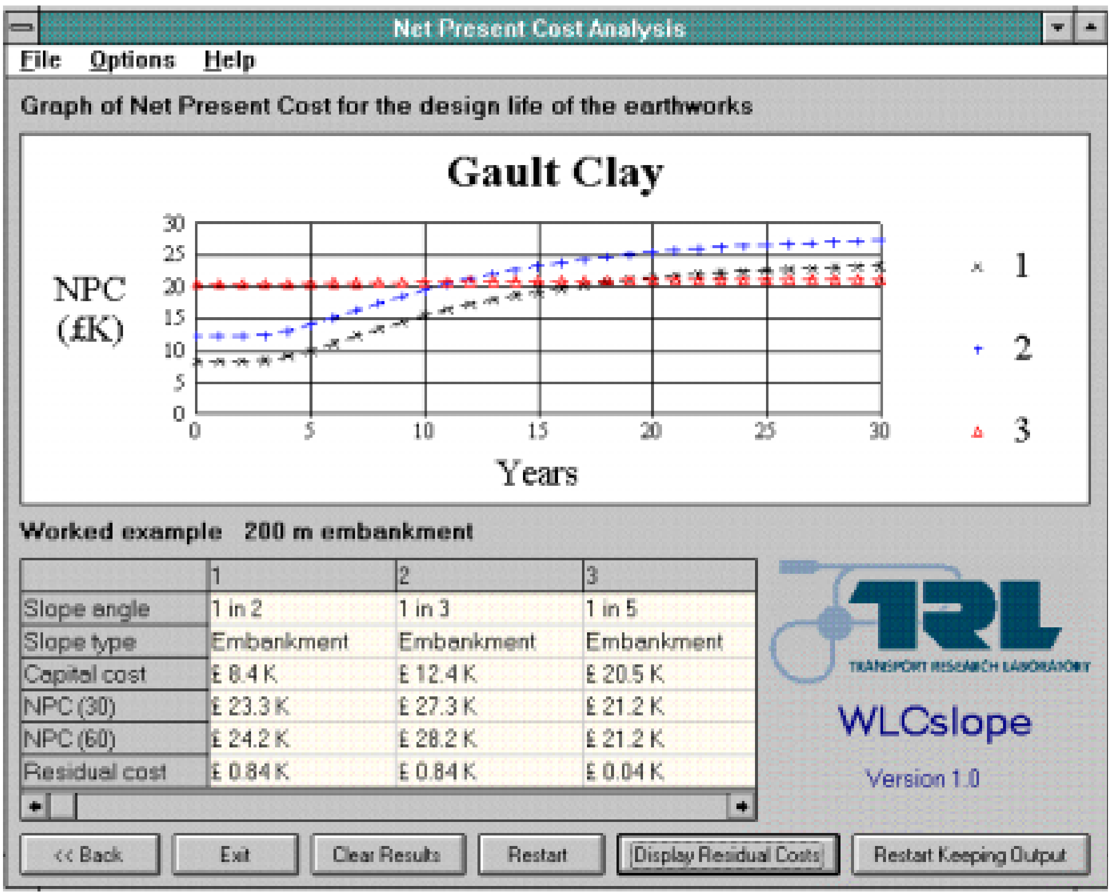
Stage 6 - Costs



Similarly to this stage in the quick cost method, default cost values are displayed by clicking on 'Display Defaults' from the | File | menu

Stage 7 - Whole life cost analysis

The results are displayed in the same way as those in the quick calculation. After repeating the analysis for the three different slope angles the final output can be viewed.



Abstract

The problem of minor slope instabilities on the motorway and trunk road network has been described by Symons (1970) and Perry (1989). The problems are mainly confined to overconsolidated clays and to particularly high sections of embankments or cuttings, but the ongoing cost of repairs to the slope failures constitutes a significant amount of maintenance expenditure. The problem of balancing construction and maintenance expenditure on earthworks slopes was addressed by the development of a whole life cost model and computer programme. The resulting programme, WLCslope, enables comparisons to be made between different design options on a whole life cost basis rather than solely on the basis of capital cost. It also allows comparison of the residual maintenance costs for different options for DBFO contracts, where the responsibility for maintenance reverts to the government after 30 years. Application of the model to a range of soil types indicates that the maintenance component of the whole life cost may be up to 3.7 times the capital cost for soils with a high rate of slope failure. In some cases, the whole life cost for a 1:5 slope may be significantly lower than that for a 1:2 slope because of the slope repair costs associated with the steeper slope. Residual costs may be in the range 5% to 10% of the whole life cost at 30 years for steep slopes with high failure rates. Variations in land price and discount rate have a major impact on the results of the analysis.

Related publications

RR257 *Determining the age of failure of motorway earthworks from aerial survey photographs* by R D Andrews. 1990 (price £20, code C)

RR199 *A survey of slope condition on motorway earthworks in England and Wales* by J Perry. 1989 (price £20, code C)

RR30 *Maintenance and repair of highway embankments: studies of seven methods of treatment* by P E Johnson. 1985 (price £20, code AA)

SR751 *Use of fabric reinforcement for reinstating unstable slopes* by R T Murray, J Wrightman and A Burt. 1982 (price £20)

LR331 *The magnitude and cost of minor instability in the side slopes of earthworks on major roads* by I F Symonds. 1970 (price £20)

CT69.1 Embankments and earthworks: design and construction update (1995-1998) *Current Topics in Transport: selected abstracts from TRL Library's database* (price £20)

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User Manual

Ground Engineering

WLCslope

Version 1.0

Transport Research Foundation Group of Companies

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Registered Offices: Old Wokingham Road, Crowthorne, Berkshire, RG45 6AU.

Contents

1 Introduction

Installation and setup

WLCslope requires a computer running Windows 3.1 or later, at least 3MB of hard disk space, a 3.5-inch disk drive and a mouse. WLCslope has been programmed using a screen of resolution 800x600. Although the program will run satisfactorily on lower resolution screens, a resolution of 800x600 or higher would be desirable.

To start WLCslope, run the installation program (setup.exe). Make sure no other applications are running. If you are running Microsoft Office and the toolbar is loaded, close it before installing WLCslope.

1. Start Windows.
2. Insert Disk 1 into drive A.
3. Choose File | Run from Program Manager.
4. Type **a:setup.exe** and press *Enter.* (Or browse for a: setup.exe)
5. Follow the instructions as they appear.

The SETUP program does the following:

- Creates a directory on your hard disk (called ‘wlcslope’ unless you specify otherwise), and copies the main program files and help files into it.
- Creates a windows application group and installs the WLCslope icon there.
- Adds system files to your windows system directory (and updates older versions of these files).

Using this manual

The User Manual has been designed to complement the on-line Help system with additional, more detailed information on specific aspects of the program. Both the User Manual and the on-line Help system are set out in the order that you would work through the program.

After installing WLCslope, read Section 2 for a brief description of the whole program, including the user input required for a successful analysis, the main program outputs, and a step by step guide to running the program.

Sections 3 to 9 describe the different stages of the analysis in more detail, providing guidance on program use and background information on WLCslope methodology.

Contacting TRL

Information on upgrades, associated publications and project reports may be obtained by contacting TRL Information & Publishing Services at:

Transport Research Laboratory
Old Wokingham Road
Crowthorne
Berkshire
RG45 6AU
Tel: 01344 770203

About WLCslope

WLCslope has been developed by the TRL to address an increasing interest in the whole life costs of constructing and maintaining the side slopes on highway earthworks. Previous work by the TRL for the Highways Agency (HA) has identified failure mechanisms for highway slopes and a database has been assembled for a wide range of slopes and materials.

Failures on the slopes of highway earthworks can undermine the road structure, damage drainage, cabling and safety fences, and in some cases obstruct the motorway hard shoulder. Reinstatement of failed slopes results in higher maintenance expenditure. This has to be balanced against the higher land take and construction costs associated with constructing slopes at angles which would not lead to future minor instabilities. A risk based approach enables a balance to be achieved between selection of the initial slope angle and the likely incidence of future slope failures. The method of whole life costing, already widely applied to road pavement and bridges design, offers an opportunity to assess these costs over the design life of the earthworks.

WLCslope is relevant for all forms of highway contract but is particularly applicable to Design, Build, Finance and Operate (DBFO) contracts as the frequency of slope failures on a national scale is increasing with time and extends well beyond the handover period. Under the terms of a DBFO contract, the DBFO consortium are responsible for building a section of highway and maintaining it for a period of usually 30 years, after which it is handed back to the HA. It is important for members of the consortium to be able to predict the likely expenditure on remedial earthworks before and after the road is handed back to the HA, and for the HA to include these future liabilities when assessing DBFO tenders from different contractors. WLCslope enables these factors to be assessed on a logical and quantitative basis.

2 Program overview

Required user input

Earthworks details – slope angle
slope type (embankment or cutting)
soil type
earthwork length
slope height

Costing details – costing period
delay period
construction and repair costs (default values are available)

Program outputs

- The whole life cost - as net present cost (NPC) - of the earthworks over the costing period in graphical form.
- Capital cost, NPC for the costing period, NPC for 60 years and the residual cost in tabular form.

Step by step guide

1 User input stage - enter the initial slope details.

2 Slope failure rate stage - The program will display the slope failure rates associated with your input data. You can accept the given failure rate or, if new data is available, you can choose to develop a user defined failure rate based on the log-normal distribution. Once the failure rate is either accepted or defined the summary page is displayed

3 Summary page - The program will request that you choose the calculation procedure to be followed for the slope geometry and costing.

4 The quick calculation procedure - The earthwork geometry and land take area will be calculated on the basis of an average section over the specified length. Once the slope geometry has been defined, the costs for land take and construction must be entered. Default values for the costs are available from the 'File' menu.

5 Detailed calculation procedure - WLCslope will request that you enter the slope height at mid section and the section length for a number of slope sections. This will enable more precise slope geometry to be defined before the capital cost is calculated.

6 Net present cost analysis - WLCslope will combine the failure rate details for the defined earthwork with the costing details and carry out a NPC analysis to produce the discounted NPC over the specified time period.

7 Options - At the output stage you can choose to run the program again (restart keeping output button), alter one or more of the input values, and compare the output. The program can be re-run up to 10 times allowing 10 sets of data to be compared. There are options to save the output data, save the output table, print the graph or print the table.

3 User input

You may enter a reference name and position for the earthworks if you wish. These will be displayed on the summary and output pages but do not form any part of the calculation.

Soil and slope types

Choose the soil type of the earthworks slope from the drop down list. There is a user defined option within this list. Select Embankment or Cutting and choose a slope angle.

The following list shows the combinations of soil and slope types available:

- Boulder Clay in cutting
- Boulder Clay with Lower and Middle Lias on embankment
- Boulder Clay with Glacial Gravel and Middle Lias on embankment
- Gault Clay in cutting/embankment
- Reading Beds in cutting/embankment
- Reading Beds with London Clay on embankment
- Oxford Clay in cutting/embankment
- Lower Lias on embankment
- Lower Lias with Middle Lias in cutting
- London Clay on embankment
- River Gravel with Reading Beds on embankment
- Glacial Gravel with Middle Lias on embankment

If a soil and slope combination that is not listed above is required, the user may carry out an analysis assuming a soil type which is known to behave similarly in order to obtain results giving an idea of the likely whole life costs. A slope angle of between 1 in 2 and 1 in 9 may be entered.

Costing and delay periods

The costing period is the period over which you require the whole life cost analysis (N years). N may be between 1 and 60 years.

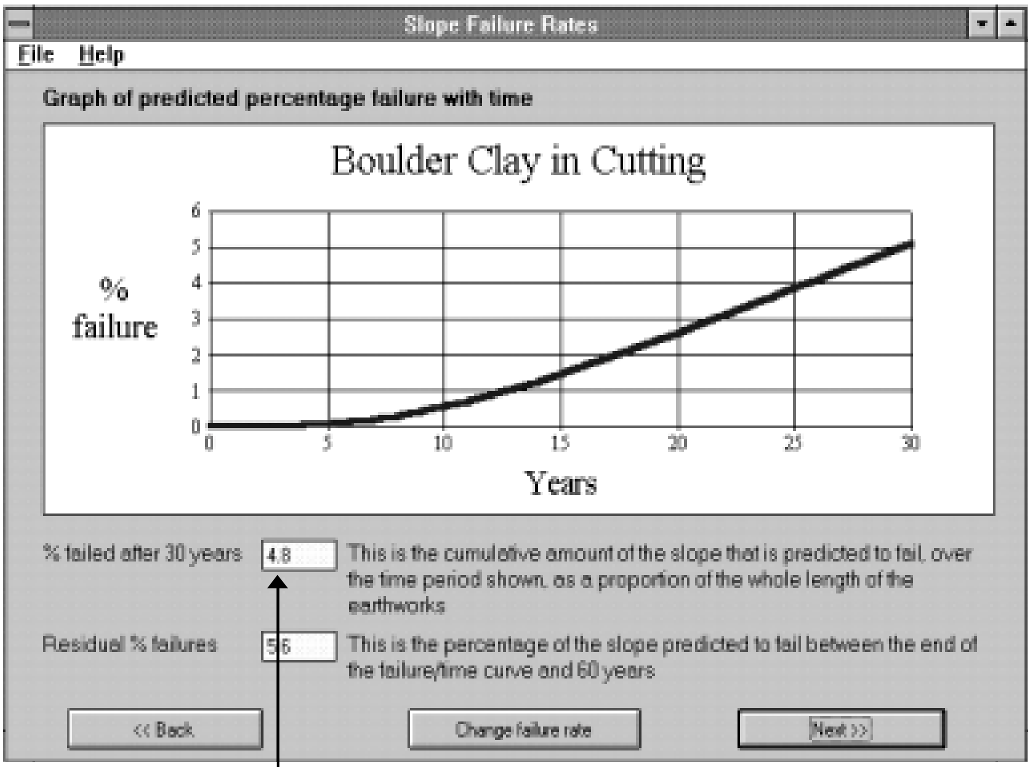
The delay period is the time between slope failure and slope repair, choose a value between 0 and 5 years. A value of 0 assumes that the slopes are repaired in the same year as the failures. A value of more than 5 years may result in the undermining of the hard shoulder and is not accounted for in this model. Using the delay period has the effect of pushing the costs back by a certain number of years and hence reduces the discounted net present cost for each year.

Options

From the File menu you can save the inputs to this page as an input file (*.inp). The saved text may only be opened within this page.

4 Slope failure rates

Percentage failure with time



The graph shows the percentage of the slope that is predicted to fail over the specified time period

This box displays the total amount of the slope that is predicted to fail within the costing period chosen at the user input stage. This prediction is derived from the TRL slope failure database. Slope failure records have been annalysed and a predictive equation developed to represent the rates of failure of slopes of different soil and slope types.

The ‘Residual % failures’ displays the percentage, by length, of the slope that is predicted to fail between the end of the failure/time curve and 60 years. The data generated at this stage will be used to determine the yearly costs of slope failures.

Options

‘Change failure rate’ allows the constants of the model to be adjusted to produce a user defined rate of failure. This option may be chosen if the user has new slope failure data which provide a better representation than the TRL data.

The graph may be printed if required.

5 User defined failure rates

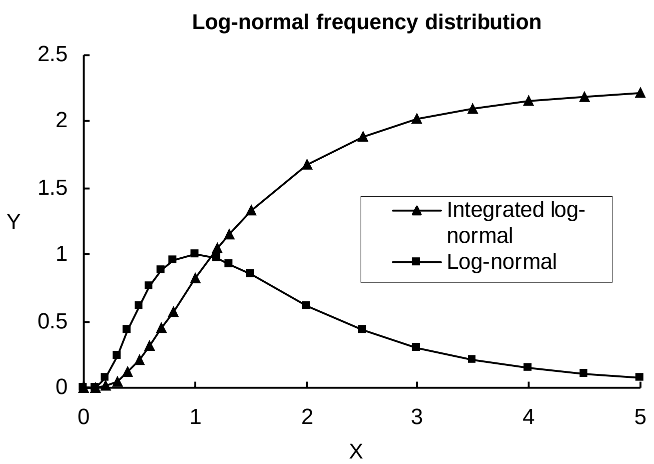
This phase allows you to define an alternative failure rate to the TRL recommended prediction by modifying the constants in the predictive equation. This stage should only be used when new data are available to show that the modified model provides a better fit.

Log-normal distribution

Log-normal frequency distribution

Cumulative distribution (integrated log-normal)

The first constant (A) denotes the maximum percentage of failures in any one year, B denotes the spread of the log-normal distribution and C denotes the position of the maximum percentage failures on the x-axis, i.e. the year in which the maximum number of failures (A) will occur.



Options

When you have changed the three constants to the required values, use the ‘Update Graph’ button to update the graph data. Use the ‘Reset Data’ button to return to the default constants for your chosen soil type. When the required failure rate is shown on the graph click ‘Next’ to proceed to the cost calculation stage.

From the File menu you can choose to print the graph.

6 Summary

The summary page displays the results of the choices you have made so far, showing; the reference labels; soil and slope type; costing period; slope angle and the failure rate model to be used in the costing analysis.

Options

There are two options to choose between for the calculation of slope volumes, land take area and slope face area. If you choose ‘ detail_calc’ you can enter slope heights and lengths for a number of slope sections; making the volume and area calculations as accurate as possible.

If you choose the ‘Next’ option, a quick calculation method based on an average slope section over the specified length of the earthwork will be used.

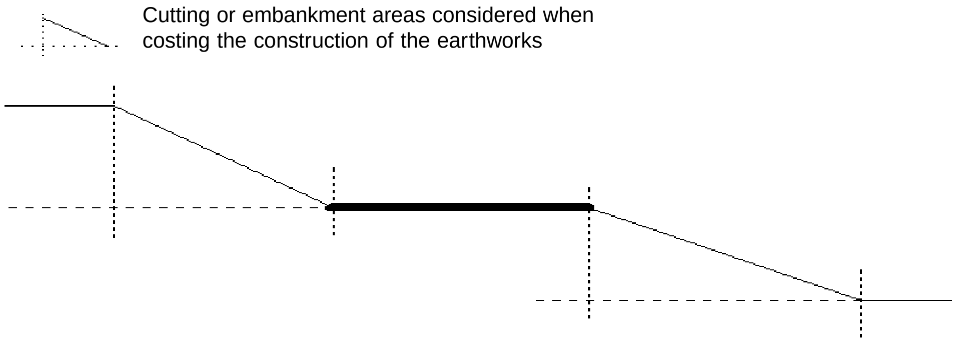
The summary information may be printed.

7 Quick cost calculation

User input

This stage requires that you enter the maximum height and the length of your earthwork. WLCslope will calculate the volume of the earthwork assuming an average section at half the maximum height. The 4/3 accounts for the curvature over the whole length of the earthwork.

The area of the slope for trimming is simply the slope face area and the land take area is assumed to be the maximum width / 2 multiplied by the length of the earthwork. Only one side of the highway (one slope) is considered in the analysis, the area considered is shown in the diagram below:



Capital cost

After entering the earthwork length and average height, enter values for the different cost items (default values may be used by clicking on ‘Display Defaults’ in the File menu).

WLCslope will use land price, excavation/deposition cost, trimming cost and percentage profit values with the chosen slope geometry to calculate the total capital cost (click ‘OK’ to view capital cost). The percentage profit is applied to the construction costs only.

Capital Cost = *Excavation (Deposition) Cost + Trimming Cost + Land Cost*

= *(Vol.*Exc.Cost) + Profit + (Trim Area*Trim Cost) + Profit*

*+ Land Area*Land Cost*

Options

Choose ‘Next’ to proceed to the Net Present Cost calculation stage where values for repair cost and discount rate are used with the % failure/time relation to give the whole life cost of the earthwork.

In the File menu, the ‘Save Costs’ item allows you to save your cost input values as *.cst files. These files may only be opened within this screen. The cost data may be printed.

8 Detailed cost calculation

This feature of WLCslope has been designed to enable you to enter detailed geometry details for an earthwork slope by dividing the slope into a number of sections.

Sections

This stage requires that you enter the number of sections that your earthwork is divided into. The maximum number of sections is 15.

You should divide the length of the earthwork which is changing in height into as many sections as possible and use one section for the length of earthwork which is at a constant height. This will ensure that the errors in volume calculations are kept to a minimum. Click ‘Next’ to proceed to the slope geometry stage.

Geometry

For each section the earthwork is divided into, enter the height at mid-point and the length. The geometry entered at this stage will be used to calculate the volume of excavation/deposition, the area of trimming and the amount of land take required by the earthwork.

A warning message will appear if you enter a slope length of greater than 50m, advising that calculations may be inaccurate if this section includes part of the slope which is changing in height.

The geometry data entered may be saved via the File menu as a *.geo file which may only be opened within this screen. This will allow you to do repeat calculations without having to enter the slope geometry every time. The section geometry may be printed. Click ‘Next’ to proceed to the costs calculation stage.

Costs

The volume of excavation/deposition, the area of trimming and the amount of land take required by the earthwork are displayed. Enter values for the different cost items (default values may be used by clicking on ‘Display Defaults’ in the File menu).

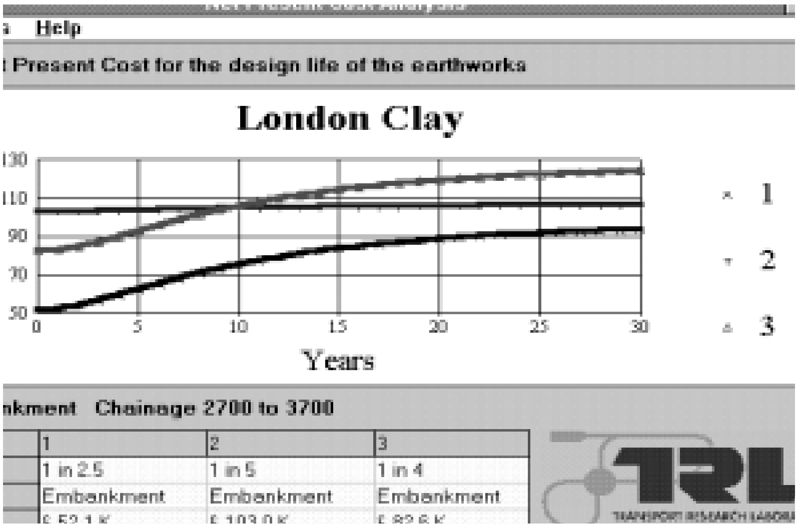
WLCslope will use land price, excavation/deposition cost, trimming cost and percentage profit values with the chosen slope geometry to calculate the total capital cost. The percentage profit is applied to the construction costs only.

In the File menu, the ‘Save Costs’ item allows you to save your cost input values as *.cos files. These files may only be opened within this screen. The cost data may be printed. Choose ‘Next’ to proceed to the Net Present Cost calculation stage where values for repair cost and discount rate are used with the % failure/time relation to give the whole life cost of the earthwork.

9 Net present cost analysis

This is the final stage of WLCslope. The program calculates the discounted, net present cost (or net present value) of the user defined earthwork over the specified time period.

Graph display



The graph shows the cumulative cost over the specified number of years.

At year 0 the cost displayed is the capital cost.

The graph-line labels correspond to the column headings in the table.

Table display

Test1 Embankment Chainage 2700 to 3700

	1	2	3
Slope angle	1 in 2.5	1 in 5	1 in 4
Slope type	Embankment	Embankment	Embankment
Capital cost	£ 52.1 K	£ 103.0 K	£ 82.6 K
NPC (N)	£ 93.8 K	£ 106.4 K	£ 124.3 K
NPC (60)	£ 96.3 K	£ 106.6 K	£ 126.8 K
Residual cost	£ 2.5 K	£ 0.2 K	£ 2.5 K

The table displays the slope angle, slope type, the capital cost, the net present cost (NPC) for the specified time period, and the NPC for 60 yeras. If required the residual cost difference between NCP(60) and NCP(N) may be displayed.

The table displays the slope angle, slope type, the capital cost, the net present cost (NPC) for the specified time period, and the NPC for 60 years. If required the residual cost difference between NPC(60) and NPC(N) may be displayed.

Analysis options

In order to compare the whole life costs of different engineering solutions for a highway slope, re-run WLCslope by clicking ‘Restart keeping output’. This will take you back to the first stage of the program where you can alter the slope angle, slope type and the delay period. You can subsequently alter costing or geometry values if you wish. Each run will produce a curve on the final graph and a column of figures in the output table.

The maximum number of curves and columns is 10. If the program is run 11 times, the 11th data set will over-write the 10th set. If you choose ‘Restart’, existing results will be lost and the analysis starts again from the beginning. The residual costs can be displayed by clicking the appropriate button. To exit WLCslope choose Exit from the File menu.

Save/print options

The options for saving the output have been designed to enable you to open the output data within spreadsheet applications. If you choose to ‘Save Graph Data’, the Y-values of the curve most recently plotted will be saved as a Text (*.txt) file. This file may be opened within a spreadsheet application so that the figures may be used to re-plot graphs. This save option will only save the data for the current analysis. For example, if you are on run 6, the Y-values for curve 6 will be saved. If you require the Y-values for all the curves, you must save the graph data after each run as a different file.

The ‘Save Table Data’ option will save the values in the table as they appear on the screen to a Text file. This file may also be opened within a spreadsheet application for further use. The graph and the table may be printed if required.

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