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Innovative Geotechnical Repair Techniques

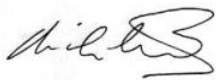

Effectiveness of Willow Poles

M G Winter, R Seddon* and I M Nettleton*

* Coffey Geotechnics Ltd

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Executive Summary

Work to evaluate the effectiveness of innovative geotechnical repair techniques for slopes has been commissioned by Highways England. The techniques are the planting of live willow poles, Fibre Reinforced Soil (FRS) and Electrokinetic Geosynthetics (EKG). These techniques were used in place of conventional approaches in order to reduce the overall impact of various challenges including environmental constraints (habitat and visual), access and utility constraints, and the need to reduce the scale and/or cost of traffic management and traffic delays.

Trials of these techniques have been undertaken over the last 20 years or so but monitoring was generally limited to just a few years post-construction. Longer term evaluation has not generally been undertaken. This report presents an assessment of the effectiveness of live willow poles as an aid to increased stability and is one of a series for this project.

The use of vegetation as an aid to slope stability has been widely written about and the associated benefits are often described as follows:

- Root reinforcement as the root structure develops, which will enhance the initial reinforcement provided by the willow poles.
- Canopy interception of rainfall and subsequent evaporation.
- Increased root water uptake of the water that does infiltrate into the soil and subsequent transpiration via the leaf cover.

Trials at the A10 Hoddesdon, M1 J12 Toddington, A5 Milton Keynes and M23 Gatwick have been assessed. It seems clear that, although monitoring was undertaken only in the relatively short-term, the planting of live willow poles has been beneficial in terms of promoting the type of changes and behaviours in the soil that would be expected and that would be beneficial from the point of view of reducing instability.

In addition to the trial sites a practical application of willow poles to stabilise a slope was examined at the M6 South of J40. At this site inclinometer readings were taken before, during and after the willow poles were installed. Progressive downslope movements of up to around 50mm were evident during a period of around 570 days before and during construction. In the 540 days post-construction these movements largely stopped and/or were reversed.

The success of both the trials and the practical application of willow poles lead directly to the recommended design guidance and specification information included herein. Lessons learned from the trials and practical application will be incorporated into that design guidance and specification in due course.

More generic lessons learnt from the trials and the practical application are reported and these are being combined with those from the reports on FRS and EKG to produce guidance for future Highways England trials of innovative geotechnical repair techniques.

1 Introduction

Work to evaluate the effectiveness of innovative geotechnical repair techniques for slopes has been commissioned by Highways England. The techniques are the planting of live willow poles, Fibre Reinforced soil (FRS) and Electrokinetic Geosynthetics (EKG) and were used in place of conventional approaches to repair in order to reduce the overall impact of various challenges including environmental constraints (habitat and visual), access and utility constraints, and to address the need to reduce the scale and/or cost of traffic management and traffic delays.

Trials of the techniques have been undertaken over the preceding 20 years or so but monitoring was generally limited to just a few years post-construction. Longer term evaluation has not generally been undertaken. This report on the effectiveness of live willow poles as an aid to increased stability is one of a series for this project.

The use of vegetation as an aid to slope stability has been widely written about and the associated benefits are often described as follows:

- Root reinforcement as the root structure develops.
- Canopy interception of rainfall and subsequent evaporation.
- Increased root water uptake of the water that does infiltrate into the soil and subsequent transpiration via the leaf cover.

Willow poles will, in addition to these benefits, provide immediate reinforcement to the slope as the poles act as either mini-piles or as short soil nails depending on the configuration of the design.

In this report (Section 2) the available information from a series of trials of the planting of live willow poles is considered for sites at the A10 Hoddesdon, M1 J12 Toddington, A5 Milton Keynes and M23 Gatwick. The information from the trials was supplemented by site visits during February and March of 2017. At this time the trial at the M1 had been removed as part of the works to reconfigure Junction 12 at Toddington and the M23 trial was about to be removed as a result of works at that site.

The trial applications of live willow poles were primarily focussed on the environmental benefits of their use to prevent shallow slope failure, but the aesthetic and ecological consequences were also considered.

The trials were informed by a precursor experiment at the A429 Iwade Bypass. The Iwade experiment yielded disappointing results in terms of the survivability of the willow poles and changes to the installation process were made for the trials. A further site planted around 15 years after the aforementioned trials was examined at the M6 South of J40.

In Section 3 an assessment of the monitoring data available for the sites is presented. Sections 4 and 5 assess the effectiveness of the trials and detail the lessons learnt. Section 6 summarises and concludes the work presented herein.

Separate reports evaluate the effectiveness of FRS (Seddon et al. 2018) and EKG (Nettleton et al. 2018). The next stage of the work will to draw the lessons learnt from the trials of each of the three techniques in order to provide recommendations and guidance to Highways England for the management of future trials of innovative techniques, whether these are

further trials of the techniques considered in the current project or of other techniques (Winter et al. 2018). The preparation of design guidance and specification information for those of the three techniques examined and considered to have the potential for future use.

2 Details and Assessment of Trials and Practical Application

Willows are believed to have been trialled as a means of stabilising slopes in the 1980s and 1990s by the National House Building Council (NHBC). A field trial of specific vegetation to enhance soil properties using vegetation was undertaken adjacent to the M20 motorway at Longham Wood near Maidstone in Kent in the late-1990s (Greenwood et al. 2004). While this trial included willow species these were in the form of peat plugs rather than poles (Hillier & MacNeil 2001).

The first experiment using live willow poles in a UK highway or road setting is believed to have been in an area of cutting on the A249 Iwade Improvement Scheme in Kent (MacNeil et al. 2001). This was only partially successful but did provide some valuable pointers for future trials and installations. Approximately 500 live willow poles were installed at the Iwade site in the late-Spring of 1996 (Barker 1997) and, while the survival rate was lower than expected at around 15% following an initial growth response of 95% (MacNeil et al. 2001), the subsequent exhumation of a number of poles in January 2000 (Steele et al. 2000) illustrated the potential of the technique with extensive lateral and vertical root development in some cases. A number of trials of willow poles were subsequently undertaken by TRL and reported by Steele et al. (2004).

Not least among the lessons learned from the Iwade experiment was that driving the willow poles led to a low survival rate and subsequent trials installed the poles into pre-drilled holes, which were then backfilled. However, it should be noted that poles were tamped into the intact ground at the base of the hole in order to aid the process of backfilling, tamping of the backfill and sealing of the top of the annulus at the top of the hole.

A number of different aspects of the trials are summarised in Table 1. All of the installations seem to have been such that the willow poles were installed vertically, even though this cannot be confirmed for the M1 Toddington trial, and the design approach is thus presumed to broadly follow the draft advice note included in Steele et al. (2004) to design for the immediate effect of the willow poles as 'short' piles.

The trial sites selected all had a history of localised shallow failures. Where more specific information is available this is detailed in the following site-specific sections of this report. While the M1 J12 Toddington willow poles trial site is no longer in existence since the junction was reconstructed published information is reviewed briefly herein.

In addition, a practical application of the use of live willow poles to improve shallow slope stability on the M6 south of Junction 40 was reviewed. This site was planted approximately 15 years after the trials.

Interrogation of HAGDMS revealed that the M6 willow poles scheme was clearly identified and that information was available for the M23 scheme albeit that in the mapping function the willow poles scheme was overlaid by more recent repairs. The M6 scheme commenced after the implementation of HAGDMS and so the details thereof would be expected to be entered in HAGDMS, as is in fact the case. For the other trial sites (A10, M1, A5), entry into HAGDMS would have relied on the trials being identified during the initial set-up of HAGDMS, which clearly has not been the case. The A10 is no longer a trunk road and as a result details for this route are no longer held on HAGDMS and, at the time of this work, HAGDMS retained the old road layout (prior to reconstruction) of the M1 J12.

Proposals have also been made to use willow poles as part of a large scale planting scheme at the A83 Rest and be Thankful site in Scotland (Raynor & Nicoll 2012; Winter & Corby 2012). At the time of writing in mid-June 2017 this scheme seems likely to be progressed by Transport Scotland and Forest Enterprise Scotland with the willow poles being planted to assist in the stabilisation of stream banks on the hillside with other native deciduous species being planted on the main part of the hillside.

Table 1: Summary features of the willow pole trials

Site	Installation Date	Slope height (m)	Slope inclination v:h (°)	Slope aspect (°)	Pole Orientation (Pole Length / Depth, m)	Hole / Auger Diameter (mm)	Pole Diameter (mm)	Installation Centres (m) H / V on Slope	Species Trialled
A10 Hoddesdon	March 2000*	5 to 6	1:3 (18)	WNW (292)	Vertical (2.3 ⁺ / 2.0)	85	Butt: 65 - 90 Tip: 40 - 60	0.75 / 1.0	<i>Salix alba</i> <i>Salix dasyclados</i>
M1 Toddington	March 2000*	6 to 7	1:2 (25 to 27)	SW (225)	Vertical (2.3 ⁺ / 2.0)	85	Butt: 65 - 90 40 - 60	0.75 / 1.0	<i>Salix alba</i> <i>Salix dasyclados</i>
A5 Milton Keynes	March 2000*	10	1:4 (14)	SSW (202)	Vertical (2.3 ⁺ / 2.0)	85	Butt: 65 - 90 Tip: 40 - 60	0.75 / 1.0	<i>Salix alba</i> <i>Salix spaethii</i>
M23 Gatwick	February 2001	3.5	1:2 (25 to 28)	W (274)	Vertical (2.3 ⁺ / 2.0)	85	Butt: 65 - 90 Tip: 40 - 60	1.0 / 0.75	<i>Salix alba</i> <i>Salix dasyclados</i> <i>Salix spaethii</i>
M6 South of J40	November 2015 to February 2016	8	1:2.5 (21 to 22)	SSW-SW (211)	Vertical (2.8 / 2.5)	150, 250, 300	Tip: 70 [^]	1.0 / 1.0	<i>Salix viminalis</i> ^{^^}

* Inferred from the commencement of monitoring, the installation date may have been slightly earlier in 2000.

⁺ Typical from site observations.

[^] Measured average of installed tops of poles.

^{^^} Species identified by supplier.

2.1 A10 Hoddesdon

2.1.1 Location and Access

The trial is located on the cutting slope adjacent to the southbound on-slip at the A10 junction with the Dinant Link Road (A10 spur) to the A1170 at Hoddesdon (Figure 1). The site is approximately 90m north of the Lord Street overbridge and is located on the upper part of the slope. National Grid Reference (NGR) TL 35878 08851 (535878 208851) locates the 'Existing tree' on the Steele et al. (2004) plan of the trial (Figure 2).

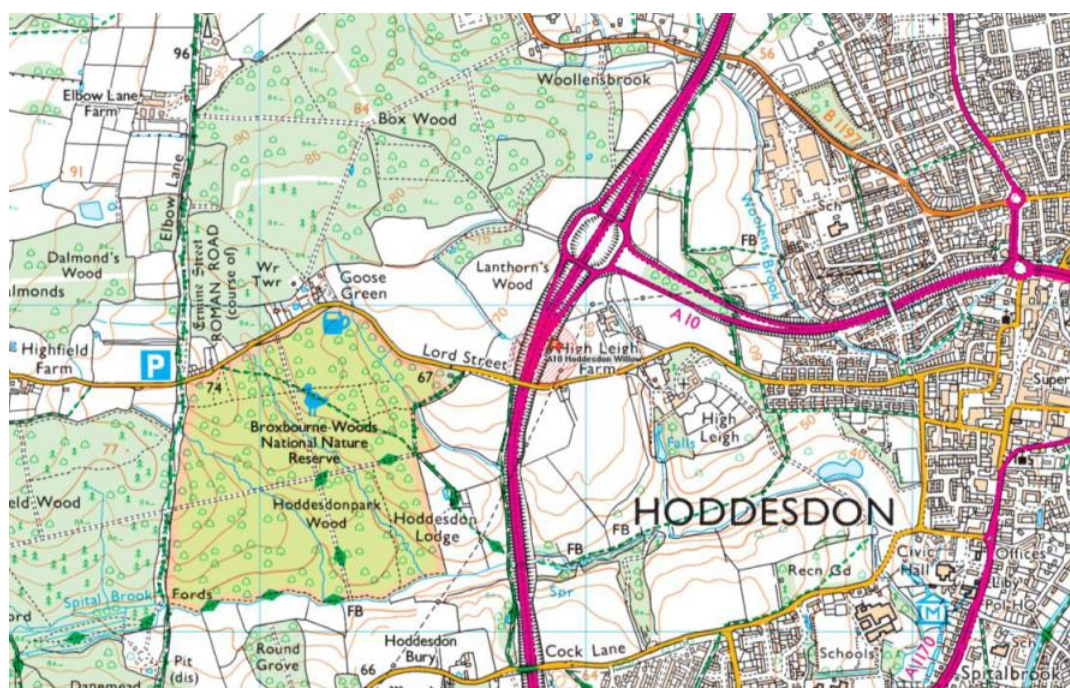


Figure 1: Location plan showing the location of the A10 Hoddesdon willow poles trial. The red flag shows the position of the trial site. (OS 1:25000, not to scale.) Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

The site was accessed by parking on the eastbound verge to the east of Lord Street overbridge using the top of the cutting slope to traverse north to the trial area.

In addition to the willow poles adjacent to the southbound on-slip, a proposal was made in 2005 (Atkins 2005) to plant the northbound off-slip with willow poles as part of slope instability remedial measures. It is not known whether this plan was taken forward, but it may have been abandoned or delayed when the A10 ceased to be classified as a trunk road. A brief visual inspection of the northbound off-slip revealed no evidence of either a trial or other systematic planting of willow poles, albeit that some remedial works must have been undertaken to remedy the encroachment of failed material on to the off-slip carriageway.

2.1.2 Site Details

Steele et al. (2004) describe the geology of the area as varied, typically consisting of.

During a pre-installation walkover survey several slips in the surrounding area were identified. The cutting height is approximately 5m to 6m at this location with a slope angle of around 18° (1 in 3) facing approximately WNW (292°). Significant shallow slips were also observed in the cutting adjacent to the northbound off-slip directly opposite the trial site.

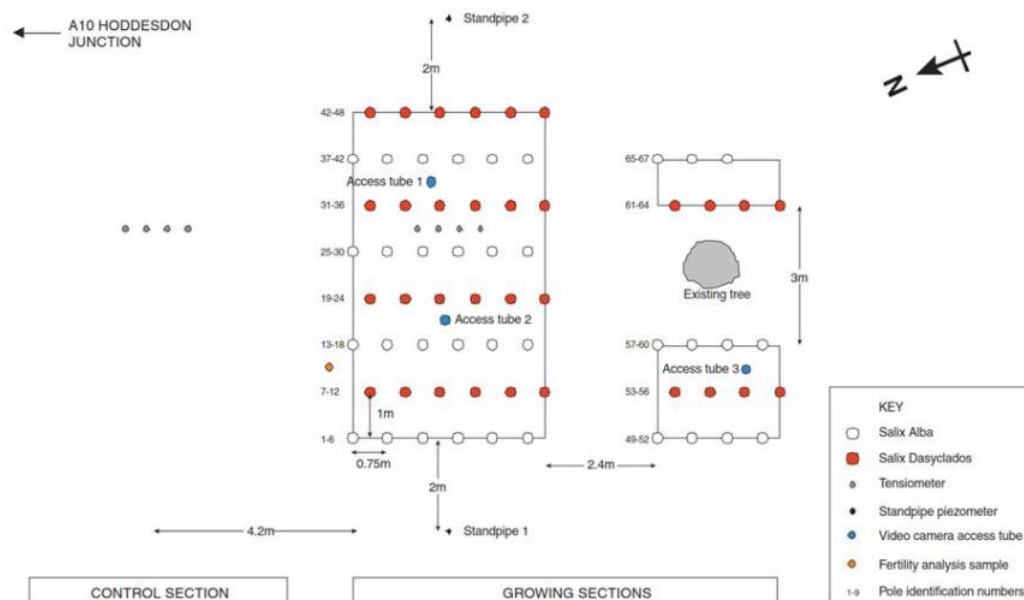


Figure 2: A10 Hoddesdon site layout (from Steele et al. 2004)

2.1.3 Inspection

The site inspection was undertaken on Wednesday 15th February 2017 in dry, overcast weather conditions with good visibility.

Signs of instability (rotational/sub-rotational movement) were observed in the area immediately to the south of the trial. The assessment of the stability of this area was complicated by extensive badger activity (Figure 3).

Similar signs of instability were observed in the trial area(s) albeit these were to some extent obscured by the willow planting. The morphology of the slope was similar in both areas with visible toe bulges and back scarps. These were less pronounced in the trial area and the back scarp was difficult to isolate. The willow pole trial is located on the upper half of the failure area thus not encompassing the toe bulge.

The trial comprised two distinct areas (see Figure 3); both areas were planted with alternating rows of *Salix alba* and *Salix dasyclados*. The smaller area, comprising five rows of willows, presented a distinct contrast between the condition and survival rate of the two species, with *Salix alba* apparently thriving (with the exception of the upper row) while for *Salix dasyclados* there was only one surviving specimen in each of the two rows. The *Salix alba* specimens towards the bottom of the slope appear to have thrived to an even greater degree with the most southerly specimen having several stems of around 350mm diameter and having reached an estimated height of around 12m (Figure 4).



Figure 3: Area to the south of the trial at the A10 Hoddesdon showing signs of instability and badger activity (Site Photograph 7DW_4076)



Figure 4: Lower part of the smaller trial area at the A10 Hoddesdon. The photograph is taken from immediately to the south of the smaller trial area and shows the lower three rows with species *Salix alba*, *Salix dasyclados* and *Salix alba* from left to right (bottom to top of slope) (Site Photograph 7DW_4077)

Judging from the amount of coppicing material deposited in the larger trial area, which comprised eight rows, the specimens in both areas of the trial have been coppiced in the

past. However, the deposition of this material within the larger trial area (Figure 5) meant that meaningful observations could not be made of the upper four rows of that area and that observations were difficult in the rest of that area.

Notwithstanding this it was clear that the larger trial area exhibited similar characteristics to those of the smaller area with the rows of *Salix alba* containing larger specimens and a greater number of surviving specimens than those rows planted with *Salix dasyclados*. Indeed, this similarity may be extended to the larger specimens being found in the lower rows of each area (Figure 6) with the stems of the specimens in the lowest row being around 100mm to 125mm in diameter. It is not entirely clear why this should be but it does seem likely that competition for either light and/or root space may play a role.



Figure 5: The larger trial area at the A10 Hoddesdon showing larger specimens in the lower row and the disposal of coppiced material, viewed towards the north (Site Photograph 7DW_4078)

The relative success of *Salix alba* compared to *Salix dasyclados* is broadly supported by the condition rating assessments carried out by Steele et al. (2004) approximately 2.5 years after planting. These assessments were undertaken during the period of the trials and, although Steele et al. (2004) did not give details of the scheme, it is important to note that the rating was only of the above ground condition of the plants.

The condition rating ranged from 1 (Best) to 5 (Failure). It seems fair to assume that as the ratings were carried out by the same personnel, the repeatability of the assessments was reasonable. However, and especially in the absence of details of the scheme used and its application, the reproducibility of assessments (i.e. carried out by different personnel) is likely to be very poor.



Figure 6: Lower part of the larger trial area at the A10 Hoddesdon showing larger specimens in the lower row and the disposal of coppiced material, viewed towards the east (Site Photograph 7DW_4080)

The small size and positioning of the A10 Hoddesdon trial, towards the upper part of the assumed failure area, suggests that the trial was designed to test the installation techniques, establishment of the willows and to determine whether the willow poles will survive and exhibit characteristics that ought to lead to improved stability, rather than to improve stability itself.

2.2 M1 J12 Toddington

2.2.1 Location and Access

The trial was located on an embankment adjacent to the northbound carriageway of the M1 to the north of J12 with the A5120. This location is just to the north of Toddington Services. The reported location of the trial (Steele et al. 2004) is between Marker Posts 62/5 to 62/8 at NGR TL 01900 29900 (501900 229900).

The junction appears to have been reconstructed sometime between 2014 and March 2016. Low resolution aerial photography (dated 2014) shows the original junction layout as was also evident in HAGDMS. Ordnance survey 2016 mapping and Google Earth™ imagery (dated March 2016) shows the new layout.

The layout of the trial is shown in Figure 7.

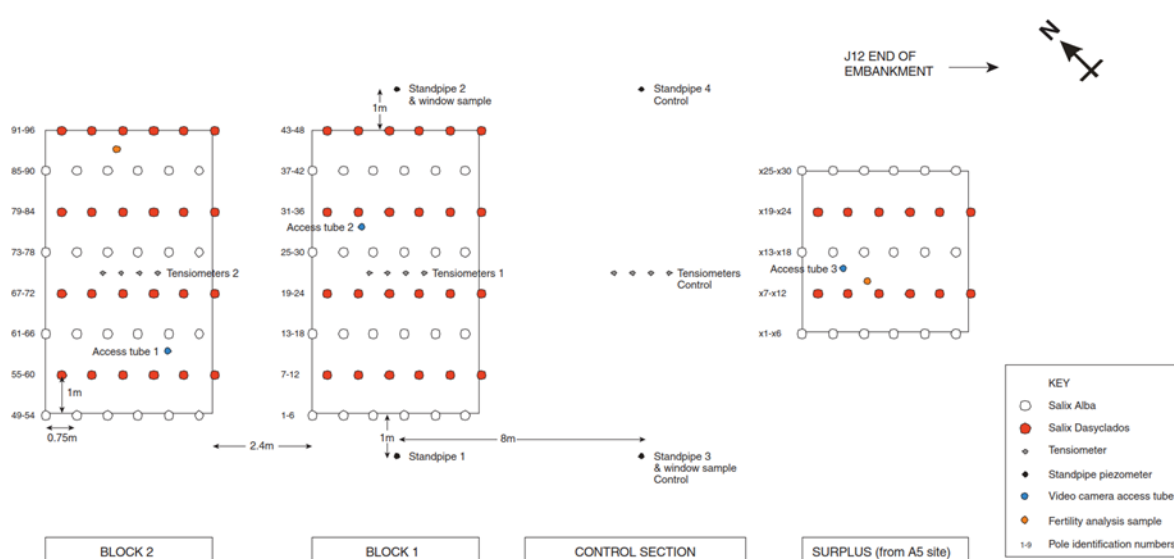


Figure 7: M1 J12 Toddington site layout (from Steele et al. 2004)

2.2.2 Site Details

This section of the M1 (Luton to Ridgmont) was opened in 1959 and the design and construction were described by Williams & Williams (1960). The embankment was constructed using locally available Gault Clay, from other areas of the works. Results from a ground investigation carried out near the location of the trial site for the proposed M1 widening, indicated that the embankment fill was a firm brown and grey mottled silt clay (Gault Clay) (Foundation & Exploration Services 1994). The embankment was constructed on a foundation of cohesive soil comprising a layer of glacial till up to 2m thick overlying Gault Clay which extended to a depth of at least 20m below ground level. The Gault Clay was generally a stiff, fissured clay which became very stiff at depth. The zone of weathering of the clay varied between about 2m to 6m depth over the site.

In the years before the trial, the site had shown signs of instability with numerous shallow slips being evident on the grassed slope, giving rise to an undulating appearance. An adjacent stretch of the slope had been used in previous slope stabilisation trials (Carder et al.

2001) which utilised the lime pile technique. The embankment height at this location was reported (Steele et al. 2004) as approximately 6m to 7m with a slope angle of around 26° to 27° (1 in 2) facing approximately SW (225°).

2.2.3 Site Inspection

A site inspection was conducted and this confirmed that the willow pole trial was no longer extant. The site inspection was undertaken on Tuesday 14th February 2017 in dry, bright weather conditions with very good visibility.

The condition rating assessments carried out by Steele et al. (2004) approximately 2.5 years after planting suggested that *Salix alba* was considerably more successful than *Salix dasyclados* which was also used at this site.

2.3 A5 Milton Keynes

2.3.1 Location and Access

The trial was located on a cutting slope adjacent to the eastbound carriageway of the A5 in Milton Keynes (Figure 8), approximately 1km west of the A422 junction and 200m west of the footbridge. The trial is located on the upper part of the slope. The location of the trial (Steele et al. 2004) is at Marker Post 80/1 at NGR SP 80995 39761 (480995 239761), which denotes the approximate centre of the trial (Figure 9). Note that the NGR given by Steele et al. (2004) is approximately 200m to the east of the trial.

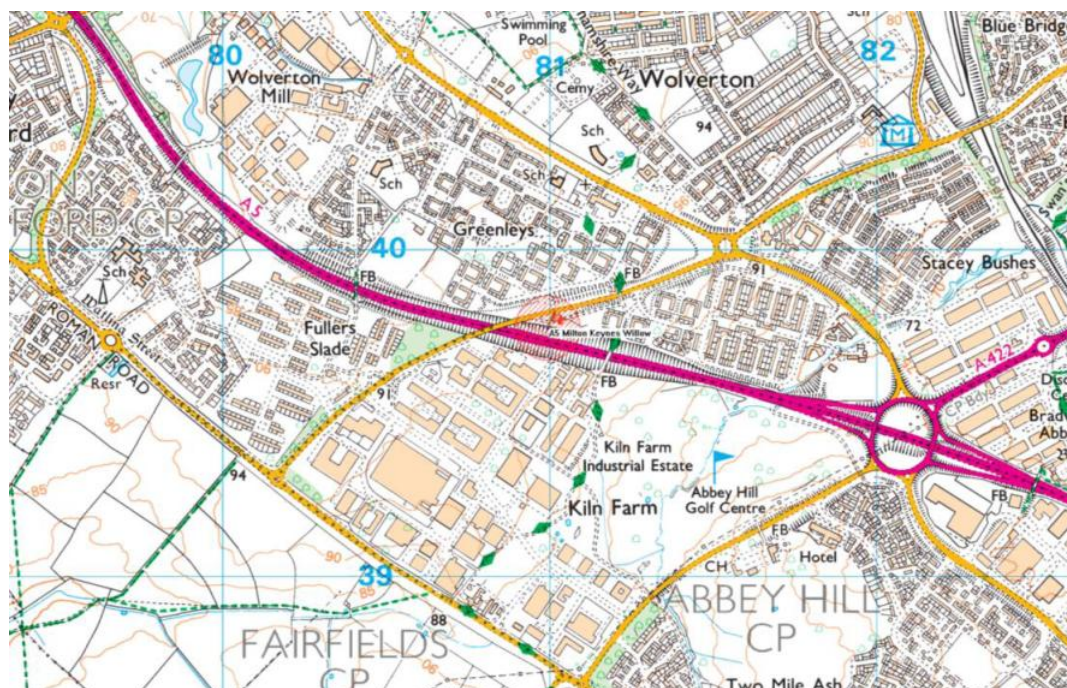


Figure 8. Location plan showing the location of the A5 Milton Keynes willow poles trial. The red flag show the position of the trial site. (OS 1:25000, not to scale.) Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

The simplest and most secure access is from the footpath that broadly parallels Millers Way and passes very close to the site (a lamp post marked F5-11-HL is located immediately above the trial site).

2.3.2 Site Details

Relatively few site details are available but Steel et al. (2004) report that the cutting was formed through a dark grey Oxford Clay. Numerous shallow translational slides were clearly evident in the upper part of half of the slope and in close proximity to the trial area.

The cutting height is approximately 10m at this location with a slope angle of around 14° (1 in 4) facing approximately SSW (202°).

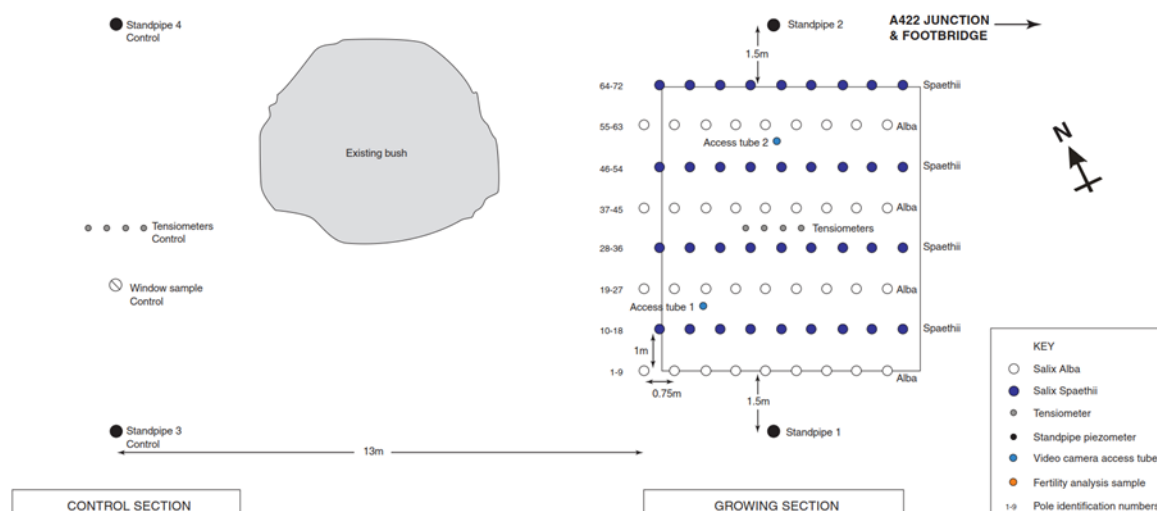


Figure 9: A5 Milton Keynes site layout (from Steele et al. 2004)

2.3.3 Site Inspection

The site inspection was undertaken on Tuesday 14th February 2017 in dry, bright weather conditions with very good visibility.

The signs of instability noted by Steel et al. (2004) were clearly visible during the site inspection although the toe bulge(s) observed during the site inspection were generally closer to the bottom of the slope than might be assumed from their description; this may mean that the movements observed by Steele et al. have developed and enlarged during the intervening 17 years or so. As with the A10 trial (see Section 2.1.3) the trial is located on the upper part of the area that shows instability and significant areas of instability were identifiable below the trial (Figure 10). Signs of surface soil and vegetation movement can be seen in Figure 10; these are typical of the slopes in and around the trial area and are potentially indicative of shrink-swell problems. Signs of instability were also noted to the east of the trial area. These were more significant than those in the trial area with a toe bulge of height around 0.5m to 0.75m and a significant back scarp. It was not possible to access the latter on site but information (unrelated to the willow poles works) in HAGDMS suggested a back scarp height of 1.5m.

The trial comprises a single area of eight alternating rows of *Salix alba* and *Salix spæthii*. Typically the surviving trees were around 2.5m to 5m in height and the rows of *Salix spæthii* seemed to have produced both slightly larger specimens and have a slightly higher survival rate than those comprising *Salix alba*; stem sizes for *Salix spæthii* specimens were typically up to around 75mm while those for *Salix alba* were up to around 50mm (Figure 11). This is also evident in Figure 12 which shows that, the *Salix spæthii* rows have developed to a somewhat greater degree than the rows of *Salix alba*.

A small number of willow poles that had apparently established successfully seemed to have rotted at the base (Figure 13). It is understood, anecdotally, that this can happen after willows are coppiced but there were no indications that any of the willow at the A5 had been coppiced.



Figure 10: A5 Milton Keynes showing the area immediately below the trial with significant signs of instability (Site Photograph 7DW_4057)



Figure 11: A5 Milton Keynes trial showing a row of *Salix alba* (left) and a row of *Salix paethii* (right) (Site Photographs 7DW_4061 [left] and 7DW_4060 [right])



Figure 12: A5 Milton Keynes trial showing a row of *Salix spæthii* (left) and a row of *Salix alba* (right) (Site Photograph 7DW_4065)



Figure 13: Specimen of *Salix alba* that has initially established but subsequently rotted at the base (Site Photograph 7DW_4069)

The relative long-term success of *Salix spæthii* compared to *Salix alba* observed in 2017 was not generally supported by condition rating assessments carried out by Steele et al. (2004) approximately 2.5 years after planting – these indicated that *Salix alba* was performing slightly better than *Salix spæthii*. However, it should be noted that the

differences between the species observed in 2017 at the A5 trial were not as marked as those observed between *Salix alba* and *Salix dasyclados* at the A10 trial.

Similar to the A10 Hoddesdon trial, the small size and positioning of the A5 Milton Keynes trial, towards the upper part of the assumed failure area, suggests that the trial was designed to test the installation techniques, establishment of the willows and to determine whether the willow poles would survive and exhibit characteristics that ought to lead to improved stability, rather than to improve stability itself.

2.4 M23 Gatwick

2.4.1 Location and Access

The trial is located on the embankment slope adjacent to the northbound lane of the M23 to the north of Gatwick Airport Interchange/Spur between Marker Posts 40.516 and 40.610 and approximately 400m north of the Smallfield Road overbridge (Figure 14). NGRs TQ 30972 43932 (530972 143932) to the north and TQ 30968 43845 (530968 143845) to the south locate the extremities of the trial (Figure 15).

Note that the NGR given by Steele et al. (2004) locates to the west of the M23 on a local road.

In recent years the upper three rows of willow poles have been removed to allow the installation of a communications trench.

The site was accessed from a works access off Hathersham Lane. The works access formed part of the ongoing construction works that will, during 2017, remove more, but not all, of the willow poles trial area.



Figure 14: Location plan showing limits of the M23 Gatwick willow poles trial. The red flags show the limits of the trial site. (OS 1:25000, not to scale.) Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

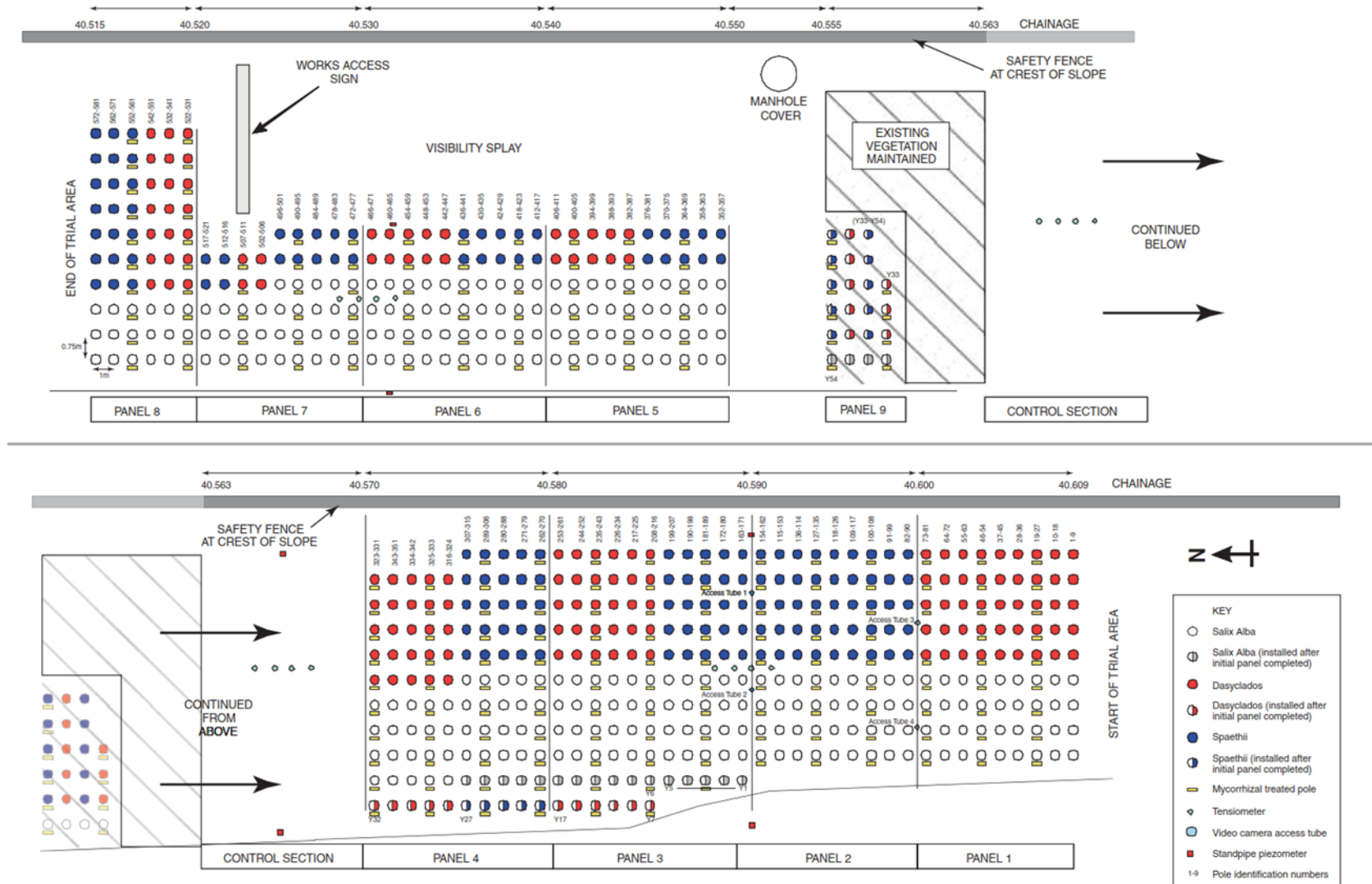


Figure 15: M23 Gatwick site layout (from Steele et al. 2004)

2.4.2 Site Details

Data from the M23 motorway desk study (Mott McDonald 1999) indicated that the embankment fill material in this area is from the Weald Clay formation and sourced from a nearby cutting. Construction of this section of the M23 commenced in 1972 and the motorway was opened in December 1974.

The embankment height is approximately 3.5m at this location with a slope angle of around 25° to 28° (1 in 2) facing approximately W (270°).

The main concern regarding instability was potential toe weakening due to saturation by water stored in the adjacent flood storage lagoon followed by loss of toe support to the slope above and mobilisation of slope failure along a plane at shallow depth (TRL 2000). The design was based on a 1m below ground level failure plane and broadly followed the principles set-out by Steele et al. (2004) and detailed by TRL (2000).

2.4.3 Site Inspection

The site inspection was undertaken on Thursday 9th March 2017 in dry, bright weather conditions with very good visibility. The first two authors of this report were accompanied by Geotechnical Engineers from Aone+.

Minor signs of instability were observed on site and Figure 16 show signs of cracking at the crest of the embankment. From discussions with Aone+ and Highways England it seems clear that this movement is a direct result of the installation of a communications trench (allowing ingress of water) towards the upper part of the embankment (approximately in line with the upper edge of the variable message sign foundation and access block). During the installation of this trench the upper three rows of willow poles were removed (Figures 17 and 18).

It is not entirely clear whether the toe softening-induced instability, noted in Section 2.4.2, had been observed at the site prior to installation or whether it was anticipated on the basis of a similar occurrence at an adjacent site (TRL 2000; Steele et al. 2004). However, no signs of movement were observed at the toe of the slope (although observation was difficult due to the density of the vegetation). It is understood that no signs of toe bulging have been observed and reported at this location since the installation of the willow poles. The M23 has been routinely inspected and no defects have been reported at the location of the willow poles other than that associated with the installation of the communications trench.

The trial at the M23 is considerably more complex and extensive than those at the A10, M1 or A5 with panels of *Salix alba*, *Salix spæthii* and *Salix dasyclados* as well as the use of mycorrhizal treated poles. The predominant species used at the M23 trial is, however, *Salix alba*, and this is even more so when the removal of the upper three rows of poles is considered (see Figure 17).

There was no clear difference in condition between the species although it should be noted that the density of the vegetation (both willows and ground cover) prevented ingress into the stands of willows. The relatively few failed specimens observed were mainly located at the base of the embankment slope. The vegetation on site has been intermittently inspected since 2006 and it has not been assessed as requiring coppicing to date, certainly

there was no evidence of coppicing having taken place (Figure 19). The diameter of the stems was typically between 60mm and 150mm.



Figure 16: M23 Gatwick trial showing crack at the crest of the embankment (Photograph courtesy and by permission of Martine Mildon, A-one+)



Figure 17: M23 Gatwick trial showing communications trench (to the right of the purple/orange conduits) and the remains of the willows that were removed during its installation. View to the north from the south end of the trial site (Site Photograph 7DW_4234)



Figure 18: M23 Gatwick trial showing Panels 5 to 8 (left to right) view to north (see also Figure 15). Only *Salix alba* is visible after the alternating panels of *Salix spæthii* and *Salix dasyclados* in the upper rows where removed to allow the installation of a communications trench (Site Photograph 7DW_4225)



Figure 19: M23 Gatwick trial. A *Salix alba* specimen at the base of the embankment showing the top of the original willow pole and subsequent shoots (Site Photograph 7DW_4238)

The results of the condition rating assessments carried out by Steele et al. (2004) approximately 1.5 years after planting showed that *Salix dasyclados* performed considerably worse than either *Salix alba* or *Salix spæthii*, with *Salix spæthii* performing slightly better than *Salix alba*. These assessments provide broad confirmation of the observations made at the A10 and A5 sites. The results also showed little to no apparent significant benefit from the use of mycorrhizal treatment in terms of the above ground species condition at 1.5 years after planting (but see also Section 3.4).

2.5 M6 South of J40

2.5.1 Location and Access

The site is located on the cutting slope adjacent to the southbound carriageway of the M6 to the south of J40. The site commences immediately to the south of the B5320 overbridge adjacent to Marker Post 80/1 (Figure 20). NGRs NY 52167 28151 (352167 528151) to the south and NY 52030 28247 (352030 528247) to the north locate the extremities of the site (Figure 21).

Access was from the B5320 overbridge which also provided secure parking.

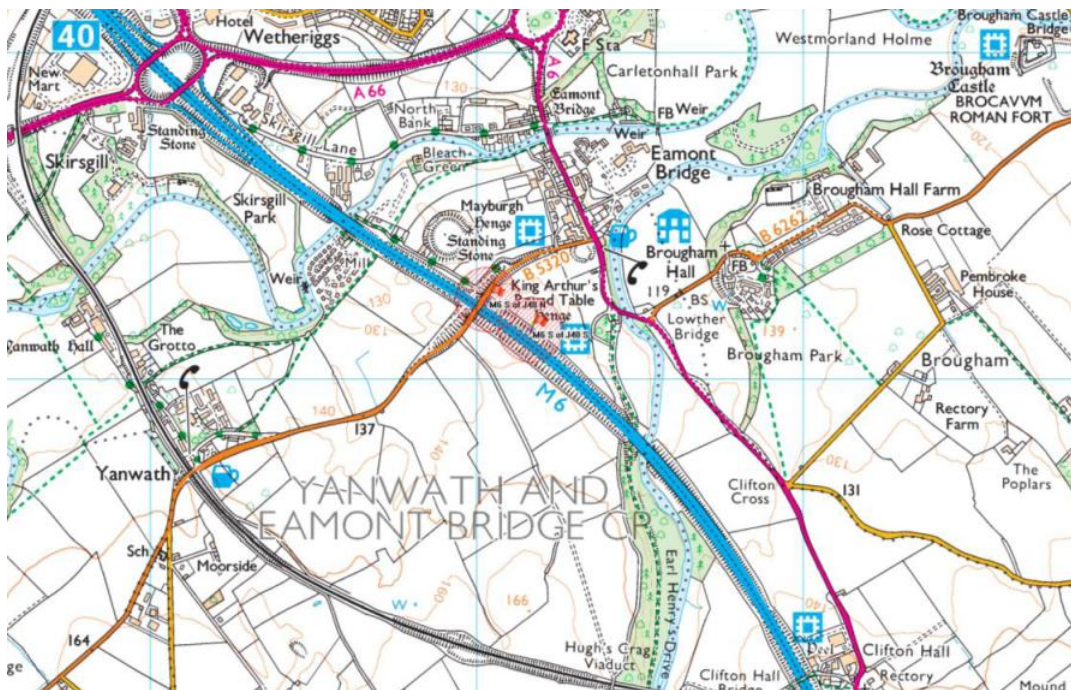


Figure 20: Location plan showing limits of the M6 South of J40 willow poles trial. The red flags show the limits of the trial site. (OS 1:25000, not to scale.) Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

2.5.2 Site Details

The cutting was formed through Glacial Till with laminated clay suspected from the outset. This seems to be confirmed in the in the GIR (EM Highways 2014) which showed a 1.5m layer of laminated clay that crops out at the toe of the slope. The thickness reduces to an estimated 0.9m below the crest of the cutting.

Shale bedrock was encountered at approximately 18m BGL and Sandstone at approximately 20m BGL.

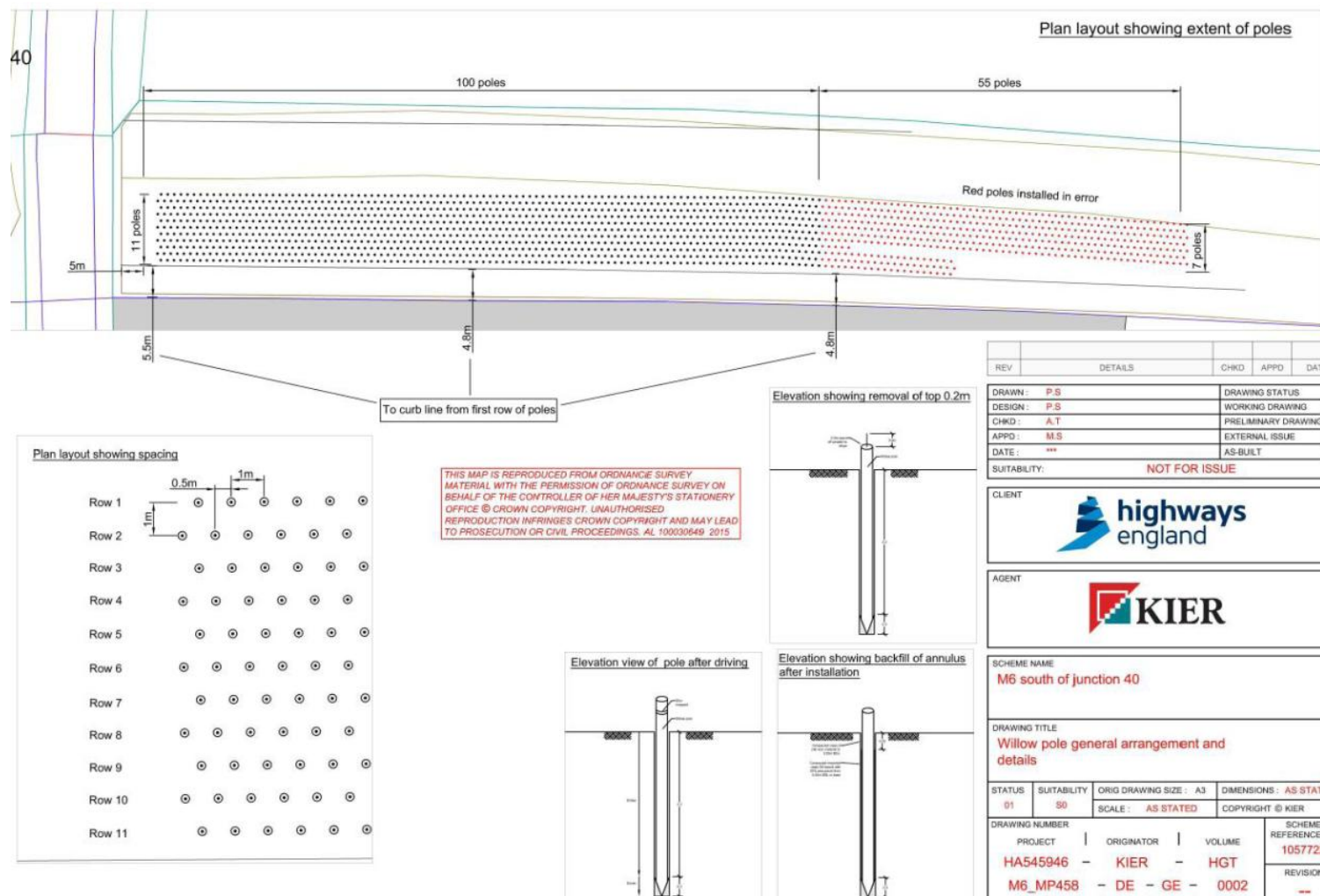


Figure 21: M6 South of J40 site layout (from Keir 2016). Note that the red tree locations on the plan were installed in error by the contractor, effectively extending the limits of the site. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

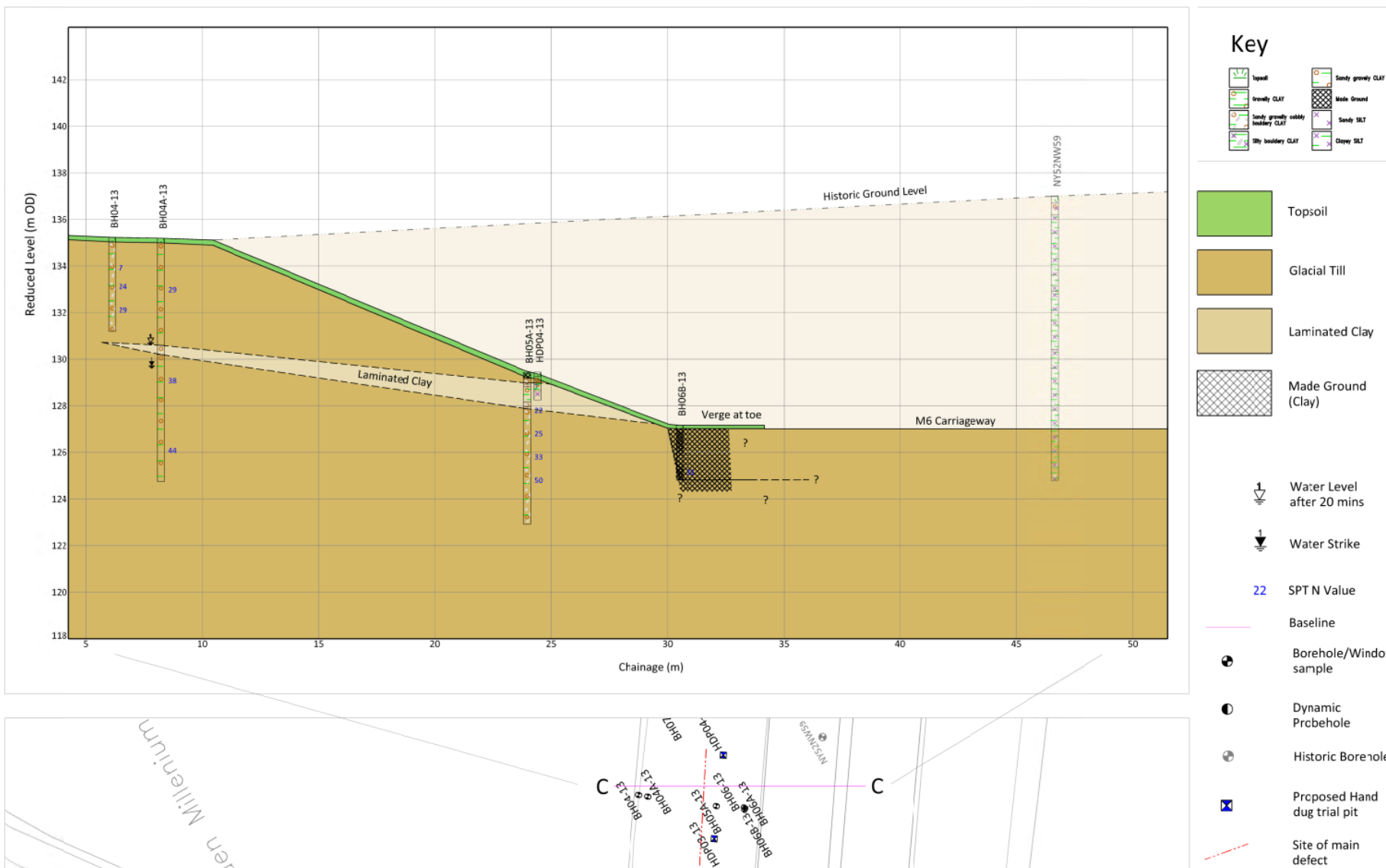


Figure 22: Section through cutting slope showing laminated clay layer (from EM Highways 2014)

The laminated clay was considered the most likely cause of instability at this location and the cutting was considered to be over steep. Design seems to have focussed on the stability of the laminated clay, not least as a toe bulge broadly consistent with the location of the laminated clay was identified as part of the investigation (EM Highways 2014; 2015) (Figures 22 and 23).

The approach to the design (EM Highways 2015) was to use willow poles augured 2.2m vertically into the ground and driven the final 0.3m to act as ‘short piles’ to resist further movement of the laminated clay, much as described by Steele et al. (2004).



Figure 23: View of the site looking southeast prior to the installation of the willow poles. The peg line defines the back scarp and the toe bulge is also visible (from EM Highways 2014)

2.5.3 Site Inspection

The site inspection was undertaken on Friday 10th March 2017 in dry, overcast weather conditions with good visibility. Figure 24 gives a general view of the site.

The toe bulge referred to by EM Highways. (2014; 2015) was readily visible with the naked eye from the B5320 overbridge (Figure 23) but is somewhat more difficult to discern from the site photographs (Figure 24) albeit that Figure 25 shows the toe bulge more clearly.

The trial essentially consisted of 11 rows of 100 poles. A planned twelfth row, closest to the toe of the cutting, was not installed due to its close proximity to the carriageway. Reanalysis of the stability of the slope unsurprisingly indicated reduced stability but that this was still at an acceptable level. The poles thus left over were installed as nine additional columns at the south end of the main part of the trial. In addition, the number of poles in most rows was increased as a result of an error during the planting (see Figure 21).



Figure 24: General view of the M6 south of J40 site from the B5320 overbridge looking south-east (Site Photograph 7DW_4242)



Figure 25: M6 south of J40, view of toe of slope looking approximately north-west towards the B5320 overbridge. The toe bulge is more discernible in this image (Site Photograph 7DW_4256)

A total of 1,549 2.8m long poles was installed to a depth of 2.5m at offset 1.0m centres both vertically and horizontally. (Note that various drawings presented by Keir (2016) specified

that the vertical spacing was 1.0m in plan, see Figure 21, and along the slope, the difference being approximately 7% to 8%.)

Figure 25 also conveys an accurate impression of the relatively immature condition of the plants, albeit that establishment seems to be progressing well and new growth was readily visibly (Figure 26). This is broadly consistent with the reported planting dates between November 2015 and February 2016 (Keir 2016).



Figure 26: M6 south of J40, new growth on the willows in March 2017 (Site Photograph 7DW_4247)

It is understood that *Salix viminalis* (osier willow) was used at the M6 site following consultation with local suppliers.

Relatively few poles that had failed to grow were encountered. However, where these were encountered significant mould/fungi growth was observed beneath the plastic spiral covers used to protect the exposed tops of the poles and shoots from animals (Figure 27). These covers seem to have inhibited shoot growth, in some cases, and it may be that they have also allowed the build-up of damp conditions so promoting the growth of the observed mould/fungi.

Mould/fungi of this nature was not observed at any of the other sites where small aperture geogrids were used to protect the poles (see Figures 4, 12 and 19 for example). This is confirmed by Steele et al. (2004) who note that at the A10, M1, A5 and M23 trials vented tree guards were used in preference to closed guards, such as those illustrated in Figure 27(R). When used at the Iwade trial site (Barker 1997) these had caused adverse desiccation

and overheating to occur. It is understood that the specification for the works required the use of a grid rather than the enclosed plastic used.



Figure 27: M6 south of J40. Growth of mould/fungi on willow poles (left) and the translucent plastic wraps used to protect the poles and shoots from animals (right) (Site Photographs 7DW_4260 [left] and 7DW_4258 [right])

During the installation of the willow poles augers of 150mm, 250mm and 300mm diameter were used. Both the 150mm and 250mm augers presented problems with tamping the backfill around the willow poles due to the small size of the annulus between the poles and the auger hole. The use of an auger with a 300mm diameter flight was found to allow for better compaction of the backfill and to increase the installation rate.

A further visit, some 18 months later, in August 2018, revealed strong growth of the willows as illustrated in Figure 28. Comparing Figure 28 with Figure 24, which was taken in March 2017, clearly shows significant growth in both height and laterally (increased bushiness). Clearly some allowance must be made for the difference season and more foliage would be expected, and is clearly evident, in August compared to March.



Figure 28: General view of the M6 south of J40 site from the B5320 overbridge looking south-east (Site Photograph 7DW_4827) taken on 28 August 2018 showing significant growth of the willows compared to Figure 24 (date 10 March 2017)

3 Monitoring Results

The monitoring undertaken at the A5, A10, M1 and M23 sites was extensive including meteorological data (sunshine, temperature, precipitation), condition rating and height measurement of the trees, tensiometer (suction) data, standpipe piezometer data, neutron probe data, and mini-rhizotron data to record root development. Invasive root investigations by exhuming the poles were also undertaken to establish root growth and to assess mycorrhizal status and to make direct measurements of moisture content (Steele et al. 2004).

The major findings of the monitoring are summarised in the sections below. As a general observation the trials did not include any direct monitoring of slope movement. Where this was conducted at the application site on the M6, the data proved to be valuable and it is recommended that future trials should directly monitor slope movement.

3.1 Climate

While placing appropriate cautions on the reporting of climate data that does not account for short-term weather events, Steele et al. (2004) reported that for the duration of the growing trial (2000 to 2003 for A5, A10 and M1 and 2001 to 2003 for M23) the climatic conditions were slightly warmer than the average, particularly with regard to minimum monthly temperatures. All sites were wetter than the average during 2000, 2001 and 2002 and drier in 2003, particularly during the growing season. Sunshine hours at all sites were generally at or below average values until 2003 when the number of sunshine hours increased markedly, coinciding with reduced rainfall and generally higher temperatures. Growing conditions were generally considered to be conducive to the growth of vegetation until 2003 when there was a marked lack of rainfall.

3.2 Plant Condition

Condition ratings were referred to in Section 2 in order to aid the understanding of the condition of the different species at the different sites. These confirmed that *Salix alba* and *Salix spæthii* poles performed well in terms of overall condition up to July 2003 (the last assessment of condition), with *Salix dasyclados* having the highest number of failures. Steele et al. (2004) also reported that the good initial growing conditions for the A5, A10 and M1 trials meant that 100% of the *Salix spæthii* poles, 97% of the *Salix alba* poles and 85% of the *Salix dasyclados* poles survived the first growing season (September 2000).

Height data was collected in July 2003, during the fourth growing season for the A5, A10 and M1 sites and the third growing season for the M23 site. As the three species grow at different rates and attain different heights at maturity a comparison of the species is inappropriate. However, comparing the growth of the individual species at different sites revealed that the height of *Salix alba* ranged from 1.4m to 5.5m after four growing seasons and that while there was some variation between the maximum height attained at each site the minimum height was less variable. Median heights were between 2.3m and 2.75m and it was suggested that the poles at the A10 Hoddesdon site were in better condition than those at the A5 and M1 sites, which broadly confirms the observations made regarding the A10 and A5 sites in Section 2.

The maximum heights for *Salix dasyclados* were similar at the A10 and M1 sites at around 3.1m but the median heights were almost 0.7m lower at the M1 site compared to those at the A10 site. Interestingly, given the observations in Section 2 of the poor condition of this species at the A10 site, it was reported that the poles at the M1 site were in comparatively poor condition.

The *Salix spæthii* poles at the A5 site obtained a maximum height of 2.8m with a median of 0.8m.

At the M23 site the trial started a year later and a direct comparison is not possible, but in terms of the measured heights there was no difference in the above ground condition of those poles treated with mycorrhiza and those not treated with mycorrhiza (but see also Section 3.4).

3.3 Suction and Groundwater

The tensiometer data presented by Steele et al. (2004) is graphic. It clearly showed the seasonal trends in suction pressures, at depths of between 0.5m and 1.5m. Higher suction pressures were evident during the spring and summer months, when temperatures were higher and the plants are active. Lower suction pressures were evident during the autumn and winter, when temperatures were lower and the vegetation became dormant and more rainfall infiltrated the soil. Comparison of the control and trial sections at each site reveal that at:

- A10 Hoddesdon that suction pressures during the growing season were higher at all depths below 0.5m.
- M1 Toddington there was no appreciable difference between suctions developed in the trial and control areas.
- A5 Milton Keynes the results were similar to, but not as marked as, those at the A10, and higher suction pressures were especially noticeable for the 2002 growing season at depths below 0.75m. In addition an earlier onset of higher suction pressures was noted for summer 2003, particularly at 1.5m depth.
- M23 Gatwick by the second growing season the suctions measured at the trial section were greater than those at the control section for depths of 1.0m and 1.5m and in summer 2003 an earlier onset and later decay of higher suction pressures was noted compared to the control section.

In addition, the data seems to suggest, for all sites, progressively (and slightly) higher suction pressures were observed growing season on growing season, although this may be unduly influenced by the drier summer of 2003.

While the standpipe piezometer data clearly showed seasonal variations there were no clear trends or distinctions between the control sections and those where willow poles were planted. Volumetric moisture content measurements made using a neutron probe confirmed seasonal variations of water content and movement but the device was not available to allow comparisons with the control sections.

In terms of the pore water pressure/suction response to the planting of willows, where the willow poles have established successfully the suction pressures at depth were increased

and that over time an earlier onset and later decay of higher suction pressures may be expected at the start/end of the growing season.

3.4 Root Development

A mini-rhizotron was developed specifically for the work described by Steele et al. (2004) to assess the development of roots. The system used comprised a downhole camera that was lowered into transparent access tubes, marked with a scale to allow root size estimation, placed adjacent to willow poles, and attached to a laptop to allow roots to be observed (and recorded) in-situ.

Roots were observed at depths of up to 2m below the slope surface and while these were generally fine roots, the results were generally positive. The success of the mini-rhizotron was limited by both water logging of the tubes, preventing observations, and by smearing of soil on the outside surface of the tube making the recognition of roots difficult (the smearing of the soil on the outer surface of the tube was reported to increase during the trial).

Invasive root investigations were also carried out by Steele et al. (2004) by means of the exhumation of willow poles at the A5, A10 and M1 sites. Extensive root structures were found to have been developed around the poles with the root system bridging the topsoil filled annulus, in which the poles were originally placed, and penetrating into the in-situ clay material. The poles were firmly located by these root systems, such that lateral movement of the poles was substantially inhibited. The distribution of the roots around the poles was also considered to be predominantly uniform, with no preference for up slope or down slope root growth. The maximum distance of root penetration was estimated to be in excess of 400mm. All of the exhumed poles showed evidence of significant penetration of roots into the surrounding soil. The majority of rooting activity was observed in the upper portion of the willow poles; the maximum depth to which rooting activity extended was 1.5m, the minimum depth to which such activity extended was 0.9m, with a mean of 1.3m.

The use of mycorrhiza at the M23 Gatwick site was also evaluated. As noted earlier, no differences between the mycorrhiza treated and untreated specimens were observed either at the end of the trial or during the inspections made during 2017. However, the estimates of ectomycorrhizal colonisation for the treated and untreated poles varied markedly with the treated poles exhibiting colonisation at the 10% to 100% level (although the predominance of results was between 80% and 100%), and the untreated at the 0% to 30% level. The lack of colonisation with the control rows suggested that crossover from plant-to-plant was very slow.

The mycorrhizal treatment was based on the use of mycorrhizal fungi which act as symbionts and are found in most biomes on earth and are a fundamental reason for plant growth and development. Such fungi, specifically Arbuscular Mycorrhizal Fungi (AMF), are primarily responsible for nutrient transfer from soil to plant. The advantages of using mycorrhizal fungi products hinge around the promotion of root growth and development and are described by Dodd (2000) as promoting an increase in the following:

- plant nutrient uptake,
- tolerance of root pathogens by the plant system,

- tolerance of water stress and adverse environmental conditions,
- efficacy of nitrogen fixing rhizobium (plant nodulating bacteria),
- plant biodiversity in restored ecosystems, and
- stability of soils.

In this context it is not surprising that the effects of the mycorrhizal treatment are not identifiable in the above ground plant structures, but that Steele et al.'s (2004) results suggested strongly that such treatment is a worthwhile addition to the practice of planting willow poles for the purposes of enhancing slope stability.

3.5 M6 South of J40

Although monitoring in the form of piezometers and inclinometers has been installed at the most recent site, M6 south of J40, at the time of writing data only to the end of the construction period was available. For the piezometer data there is no discernible trend while the inclinometer data showed downslope movements. The recorded downslope movements (Keir 2016) as of March 2016 varied from approximately 50mm at the surface to just over 10mm at 2.0m depth over around 570 days (Figures 29 and 30).

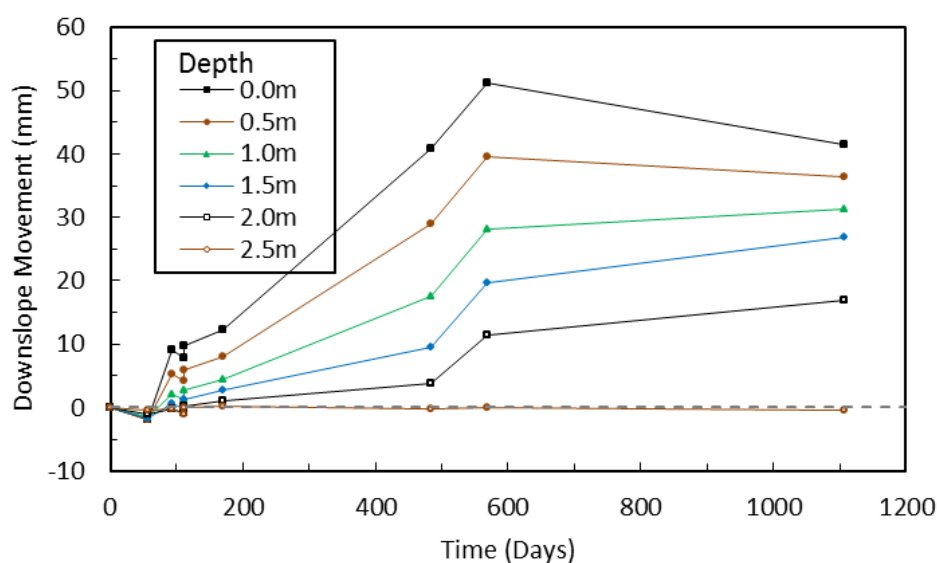


Figure 29: Downslope movement measured using an inclinometer at BH05A/13 at the M6 South of J40 site showing movement with time at different depths

The movements observed showed reasonable coincidence with the estimated depth of the laminated clay layer that the work was intended to stabilise (Figure 30) and movement is clearly increasing with time (Figure 29) until after the completion of installation (readings dated 10 March 2016) with little to no movement recorded between that reading and the sole subsequent reading (dated 30 August 2017). The data strongly suggest that the use of willow poles has effectively stabilised the slope, at least in the short-term. Notwithstanding this the shape of the final set of readings relative to the previous readings may suggest that the movement is being forced deeper as a result of the willow poles, but this is considered relatively unlikely. Further monitoring is recommended at six monthly to annual intervals

over a period of 20 years after the end of construction, a period that is meaningful in terms of slope instability, in order to evaluate the long-term effects of the willow pole stabilisation and to ensure that the movements do not continue at a deeper level.

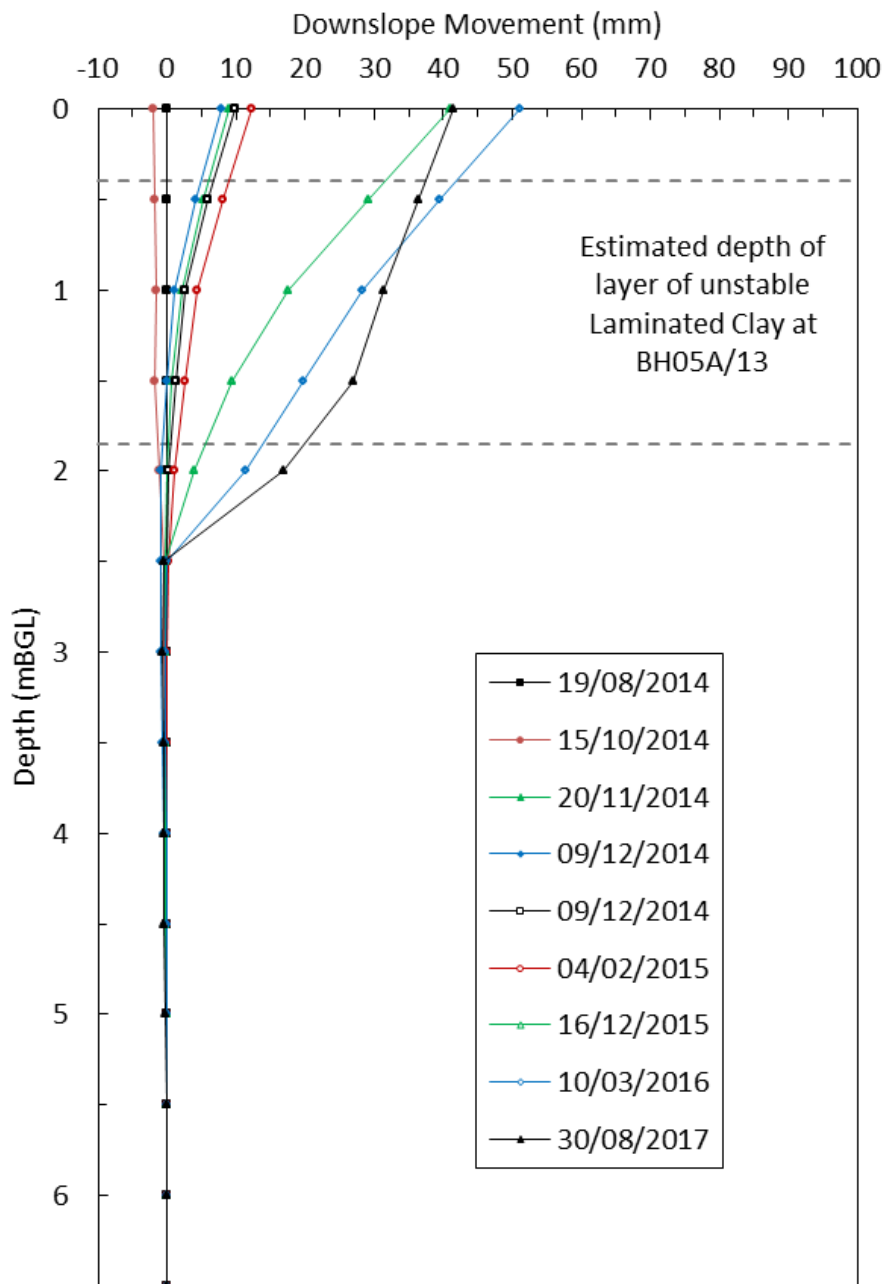


Figure 30: Downslope movement measured using an inclinometer at BH05A/13 at the M6 South of J40 site showing movement with depth at different times

The data presented by Keir (2016) suggest that the inclinometer measurements ranged between 0.5m and 7.0m, however when the data was reanalysed using Soil Instruments In-Profile™ software the data ranges for all of the measurements, including those for 30 August 2017 were reported as 0m to 6.5m. This latter depth range has been adopted for reporting herein. This range shows a slightly better correlation with the estimated depth of the laminated clay layer. However, it is important to note that the most important issue here is not the depth of the readings but the movements observed in the slope over time.

It should be noted that although it was planned that monitoring would continue after construction this did not happen perhaps, in part, due to a major change in the way in which Highways England operates in the area until this project requested such readings.

4 Effectiveness of Trials

Issues surrounding the clarity of the purpose of the trials and thus the measurement of their success or otherwise are discussed in Section 5. The small size and positioning of the A10 Hoddesdon and A5 Milton Keynes trial sites, towards the upper part of the assumed failure area, suggests that these trials were designed to test the installation techniques, establishment and survival of the willow poles, and to determine whether they exhibit characteristics that ought to lead to improved stability rather than to improve stability itself. Although the site was no longer extant, the available information regarding the M1 J12 Toddington site suggests that a similar conclusion could be drawn about that trial.

The observations of these trial areas and the monitoring results presented by Steele et al. (2004) indicate that these trials were successful within those parameters; certainly the A10 and A5 trials show that willow poles can be successfully installed and that they both establish in the short-term and grow in the longer term. Indeed the success of some of the *Salix alba* specimens at the A5 site, some very large specimens were observed, strongly suggests that a much greater focus on planned periodic maintenance is required.

In addition, these trials allowed three species of willows to be trialled. Judging from the results derived from condition rating assessments the species *Salix dasyclados* would not have been used in subsequent trials. Notwithstanding this, it seems clear that these results would not have been available and/or be sufficiently robust to exclude this species from the M23 Gatwick trial which was installed approximately one year later.

The M23 Gatwick trial was of a much greater scale and rivals the subsequent and relatively recent application at the M6 South of J40 for scale. However, the M23 site had discrete panels of the three different species of willow pole and also trialled the use of mycorrhizal fungi inoculate on every third column of poles installed. Steele et al. (2004) give details of the treatment but it is essentially intended to increase the resilience of the resulting plants and to improve the root structure in terms of their thickness and proliferation of finely divided lateral roots. The work undertaken by Steele et al. (2004) indicated that the mycorrhizal treatment led to better and root growth. Notwithstanding this there was no evidence of such additional growth being manifested as increased growth above ground, an observation that conforms with observations in March 2017 at which time it was not possible to identify the treated specimens.

This then begs the question, were these trials effective? A qualified 'yes' seems to be an appropriate answer for the A10 and A5 sites with no conclusion possible for the M1 site as it is no longer in existence. The trial monitoring results and the observations made in early-2017 strongly suggest that the planting of live willow poles will promote changes and improvements in the soil mass that should improve stability. There is also a verified approach to design and construction leading to improved mechanical stability and data from the M6 South of J40 strongly suggests that the use of willow poles has effectively stabilised the slope, at least in the short-term

For the M23 site the installation of live willow poles was specifically targeted at the potential for instability caused by toe-softening and, in the absence of any evidence of this, the trial may be deemed a success.

5 Lessons Learnt

The lessons that can be drawn from this work relate to both the structure and formulation of trials in general and to specific issues related to willow poles.

5.1 General

There are issues surrounding the purpose of trials and thus the ability to effectively measure and quantify or qualify their subsequent success or otherwise. In the Foreword to the seminal book on geotechnical instrumentation (Dunnicliff 1988), Ralph Peck wrote that *“Every instrument ... should be selected and placed to assist in answering a specific question. Following this simple rule is the key to success ...”*. A similar approach can and should be taken to trials of innovative geotechnical repair techniques. To this end, a clearly stated purpose is a prerequisite; subsequent criteria against which success or otherwise can be measured are only slightly less essential.

The purpose of the willow pole trials seems evident but was not clearly stated. In the case of the A10 Hoddesdon and A5 Milton Keynes trials the purpose seemed to be to determine whether the willow poles will survive and establish over a reasonable two to three year period and that the plants and soil responded in a way commensurate with the expectation that stability would be improved. The M23 Gatwick trial was at a much larger scale and it seems clear that it was predicated on making a real contribution to stability at the site. Given that no movement resulting from toe-softening was observed, it seems fair to judge the trial a success. However, there is no movement or deformation from this, or adjacent site(s) that may have experienced such movements, in order to validate this apparent success.

It is important for future trials, whether of willow poles or any other innovative technique, that the purpose and limitations of the trial are clearly set-out at the start.

The monitoring was conducted for only two to three years. This seems to allow a clear indication that the technique, in this case the planting of willow poles, is having the type of effects that would be anticipated and is not causing unexpected problems. However, given that the onset of instability is usually a slow process and that the growth and establishment of vegetation are also slow processes this time frame for monitoring was clearly insufficient. In order to fully evaluate the effects of the treatment a monitoring period of 15 to 20 years is recommended for future trials, albeit that monitoring intervals need not be overly frequent. A caveat is that if the monitoring frequency is insufficiently frequent, then problems with continuity of process, people and data can come to the fore and it is recommended that a frequency of no greater than 24 months be maintained.

5.1.1 Location and Access

At a more prosaic level, determining the precise location of, and safe access to, the trial sites has on occasion proved problematic. The main willow pole trials were constructed around 2000 to 2001. Since that time, the ability to rapidly capture locational data using

low-cost, high accuracy GPS (and indeed mobile telephones) has been transformed¹. It is a simple matter to automatically generate an accurate NGR at a given location either when in situ or later using Ordnance Survey mapping to pinpoint a location.

It is recommended that the reporting of future trials should include the trial location expressed both on an Ordnance Survey map, either 1:50,000 and/or 1:25,000 *and* any other scale deemed suitable, and as both alphanumeric *and* fully-numeric NGR(s) of one or more salient locations (e.g. NY 52030 28247 and 352030 528247).

In addition, the safe access for observation, monitoring and maintenance should be clearly reported with an indication of a safe area or areas for parking and, where appropriate, a walking route to the trial site itself should be defined. Any constraints regarding the need to obtain permission from landowners should also be itemised.

It is considered that these items should be recorded in the Geotechnical Feedback Report (GFR), which is routinely placed in HAGDMS. It is recognised that the access may change after the trial. However, this could be readily updated by means of a short, supplement to the GFR and be placed in HAGDMS as necessary. This is especially important where the trial may be undertaken in combination with a larger scheme. For example, Willows Poles may be planted to improve a potentially marginal section of a cutting where adjacent sections are regraded and subsequently replanted. If the location of the Willow Poles is not carefully defined then they may get 'lost' as the adjacent trees mature.

5.2 Specific

5.2.1 Willow Species

It is important to note that the long-term sustainability of the reinforcing provided by the poles is very much dependent on the survival and establishment of the plants and thus the consequential development of additional the rooting structures and root water uptake. If the plants do not survive then the poles themselves will, over a period of time, rot, lose strength and become ineffective in providing reinforcement, and potentially provide a preferential path for water ingress to the slope.

Four species were used as part of the willow pole trials and practical implementations described in this report. *Salix alba* (white willow) and *Salix viminalis* (or osier, common osier, basket willow) are native species. *Salix dasyclados* appears to be native to China and *Salix spaethii* is grown as an energy crop that is coppiced regularly; neither seems to be native to the UK. Advice from Highways England's Environmental Advisors suggests that, whilst they are not precluded from planting non-native species, as part of Government they are committed to plant native tree species other than in exceptional situations. While it may be argued that slope stabilisation is an exceptional situation, the trials demonstrate no advantage to planting with *Salix dasyclados* and that *Salix spaethii* is generally similar in

¹ The US Defense Department ended the deliberate degradation of GPS signals in 2000, with the popularisation of personal GPS devices beginning in 2001; 'assisted GPS' technology, which supplements the GPS signal with mobile telephone signals to improve accuracy, followed in 2004 with many improvements since.

performance to *Salix alba*. Further *Salix spaethii* and *Salix viminalis*, the latter of which was used at the M6 South of J40, are generally grown for energy cropping and basket production, respectively. Both therefore require frequent coppicing and it may be that the two species are similar although further work would be required to fully confirm this.

It is important to select willow cuttings from parent plants that are adapted to the soil conditions on site; for example, riverbank types will not survive on exposed dry slopes. This is especially important in the context of climate change which is, for example, expected to lead to dry slopes in the south-east of England and the potential for vegetation stress during the summer. It is also important to note that willow cannot be grown from seed and so the approach using live poles requires a ready supply of parent plants. The feedback from the M6 site further emphasises the need for consultation with local suppliers and other experts to establish the most suitable species in the local conditions of the site and, of course, the availability of suitable poles.

It is clear that advice on the selection of appropriate species and potential sources of supply must be sought from Highways England Environmental Advisors and/or a qualified Arboriculturist at an early stage of any proposal to use willow poles as part of a slope repair project. The selection of appropriate species should take full account of climate change.

5.2.2 Design

The trials conducted in 2000 and 2001 allowed Steele et al. (2004) to draw a number of conclusions regarding design for the use of live willow poles. They concluded that live willow poles offer an easy, relatively rapid and cost effective method of ensuring that vegetation is successfully established both at surface level and at depth within a slope. In each of the trials, the poles formed dowels to provide immediate improved stability and can be used in the prevention, and repair, shallow slip failures on both embankments and cuttings. As the root system becomes established over time, benefits to the stability of the slope increase through additional root reinforcement and root water uptake leading to a reduction in the soil moisture content. Steele et al. (2004) also suggested a potential benefit in terms of the reduction of the tendency for soil creep resulting from seasonal swell/shrink cycles in clay soils. This is not supported by any specific data and more recent work (Smethurst et al. 2015) suggested that this benefit may not be realised and that the presence of trees may increase shrink swell and associated movements.

Willow pole stabilisation is generally designed on the basis that the poles act as dowels or mini piles/micropiles (installed vertically) or soil nails (installed normal to the slope surface) and with little to no allowance being made for the reinforcing effects of further root development, canopy interception or root water uptake. This conservative approach seems sensible as both these effects are notoriously difficult to quantify and are temporally variable. Willow poles must be inserted to a depth that exceeds the likely failure surface, typically this will be a depth of between 1.5 and 2.0m and thus limits the technique to relatively shallow slope failures.

Useful advice on the approach to design, and the design parameters and their values for willow poles is also given by Steele et al. (2004).

Steele et al. (2004) noted a number of potential positive stability effects including the effect on shear resistance of the cross-sectional area of the poles that intercept the shear plane;

the fact that the toes of the poles are embedded in lower, stable strata introducing arching between the poles; the effect of the poles acting as laterally loaded piles; and the effect of the root structure. They also noted that evapotranspiration will act to reduce groundwater levels (and moisture content) of the soil and, while they do not mention canopy interception specifically, this is implicit. They also note that the hydrological factors will be most significant in the summer months when the willows are actively growing.

While Steele et al. (2004) allude to the potential to plant willow poles at an angle such that they act as soil nails (i.e. in tension), neither trials nor applications appear to have been conducted to test the feasibility of such an arrangement.

5.2.3 Construction

5.2.3.1 Installation

Willow poles can be either driven into the slope or can be placed in pre-bored holes. The trials were informed by a precursor experiment at the A429 Iwade Bypass. The Iwade experiment yielded disappointing results in terms of the survivability of the willow poles; this was largely attributed to the fact that the poles were driven into the ground and to unfavourable weather conditions immediately after planting. Consequently all of the trials, and known applications since, have installed willow poles in pre-augered holes with only a limited amount of driving in order to 'socket' the base of the poles. The driving of willow poles is not recommended

The use of an auger with a flight diameter of 300mm or greater allowed for better tamping of the backfill in the annulus around the pole and sped the progress of the installation. Smaller diameter augers were found to be less effective at the M6 site.

5.2.3.2 Tree Guards

Vented tree guards, such as narrow aperture geogrids, should be used to protect to prevent damage by pests. At the M6 south of J40 site this was specified but an alternative transparent plastic was used; this seems to have caused the growth of fungi. This suggests that a stronger approach to ensuring that the specification is met during construction may be required.

5.2.4 Design and Construction Costs

The total costs of design and construction using live willow poles are presented by Steele et al. (2004). These were for relatively small installations and design costs were available only for the M23 Gatwick site. Costs of between £50 and £87 per willow pole were estimated by Steele et al. (2004) at 2000/2001 prices. At 2017 prices this corresponds to around £90 to £155 per pole installed (using a standard 3.5% discount rate).

However, the design costs are clearly not proportional to the number of poles installed and for larger scale installations these costs may be less.

Costs given by Keir (2016) are insufficiently detailed to develop a contemporaneous cost estimate but materials and plant suggest costs, excluding labour and design, of around £20 per willow pole.

5.2.5 Monitoring

Steele et al. (2004) presented extensive monitoring results from the willow pole trials. Of those the climate data provided useful background while the piezometer data provided relatively little value as differences between the planted and control sections could not be established. This was in contrast to the suction data, as measured using tensiometers, which clearly showed the effects of the willow poles on soil suction. Of particular value were the plant condition rating data that gave an invaluable framework around which to set the observations that were made during the site visits undertaken for this work during early-2017. The monitoring of root development demonstrated that the willow poles grew in an effective manner and as might be expected. Most importantly, this also demonstrated the efficacy of the mycorrhizal treatment in terms of the promotion of root growth and development, albeit that the benefits were not found to be apparent in the above ground plant structures either at the time of the trial or in 2017.

Monitoring of slope movement and deformation was not carried out at any of the trial sites. This seems likely to be due to the lack of specific instability features being targeted for remediation. It is considered that for future trials and installations of willow poles direct monitoring of slope stability is required; this would usually be achieved using inclinometer(s).

Where a specific instability was targeted at the M6 South of J40 the associated movement monitoring (using an inclinometer) clearly demonstrated the pre-installation movement and also the decrease in the movement post-installation to a point where it is not unreasonable to assume that the movement has been stopped, at least in the short-term. Notwithstanding this there is a suggestion that the movement might have been slowed and driven deeper in the slope, although this is considered relatively unlikely.

The post-construction monitoring was undertaken only as a result of requests related to this current project and it is vital to ensure that post-construction monitoring continues in both the short-term and over a longer period to assess the longer term effects of willow poles stabilisation. On this theme the monitoring at the M6 South of J40, particularly the monitoring of movement with inclinometers, should continue for a minimum period of 20 years following the completion of construction in order to acquire data over a period of time that is meaningful in terms of slope instability.

5.2.6 Management and Maintenance

Willow poles are fast growing and, while some species grow at a greater rate than others, coppicing must be an integral part of any willow pole scheme intended to promote stability. In addition to the species planted, the frequency of coppicing is likely to depend on climate and other factors related to growing conditions and is thus likely to be variable.

Coppicing helps to prevent the trees from becoming too tall, which is an issue as willow is prone to becoming brittle as it ages and can grow to become large specimens (see Figure 4).

Coppicing maintains trees at a 'juvenile' stage of development preventing issues associated with age.

Regular visual inspections will be required in order to assess the future need to coppice as well as to assess the health of the plants and therefore the likely success of the scheme. The need for coppicing must be assessed by an appropriately qualified and experienced Arboriculturist. Annual inspections are envisaged in the first three years after planting with coppicing likely to be needed after five years or longer; it is recognised that this is strongly site dependent and the willows at the M23 have not required coppicing after more than 15 years. Coppicing, when required, should be undertaken in three coupes such that one in three plants is coppiced in each of three successive years.

In addition, maintenance to eradicate competing vegetation, including grass, may be required in the early years as the willows establish (Hillier & MacNeil 2001). It is suggested that this be undertaken annually in the first three years after planting in order to maximise the chances of success.

The frequency of inspections and maintenance after the first three to five years should be determined on the basis of arboriculture advice and take full account of the site, the species planted and the development of the plants to date.

Notwithstanding the timings and frequencies of inspection and maintenance activities suggested above, there must be a degree of flexibility built into such activities. It is certainly not appropriate to coppice, or cut grass, simply because the specification suggest that it may be necessary. Such activities must be undertaken on a 'needs' basis and be determined on the basis of appropriate arboricultural advice with the activities fully-integrated in to the Landscape Management Plan.

Constructive uses for the coppiced products should be sought. These might include making the material available to manufacturers of baskets and other woven willow products (withies), the creation of willow brush river bank erosion control mats (e.g. Kayser et al. 2015), its use as poles for future willow poles slope stabilisation schemes if poles of an appropriate size can be generated, or the creation of fauna habitat on appropriate sites. The frequency and timing of coppicing may also be influenced by the intended destination of the coppiced products.

Both the costs of inspections and those associated with coppicing must be considered in terms of the potential for future willow pole schemes.

5.2.7 Life Cycle Assessment

A cradle-to-site Life Cycle Assessment (LCA) has been conducted for the three techniques – willow poles, FRS and EKG – and a crushed granular fill control technique. The results of the LCA are reported in detail by Leal et al. (2018) and included consideration of two failure depths of 1.0m and 2.5m (the 1.0m failure depth was not considered for EKG) and various transport distance options. It was found that at both failure depths, and for all transport cases, the greatest environmental impact was for the Granular Rock Fill Replacement control. At 1m and 2.5m failure depths this technique resulted in an impact of 51 to 80 kgCO₂e/m² and between 109 and 174 kgCO₂e/m² of failed slope respectively, depending upon the transport distance assumed.

Willow Poles had the least impact, resulting in 4 to 8 kgCO₂e/m² to 8 to 12 kgCO₂e/m² of failed slope respectively. For the 2.5m failure depth EKG was the second best performing technique, with an average impact of 14 kgCO₂e/m². FRS had an impact ranging between 16 and 35 kgCO₂e/m². For techniques requiring large quantities of materials and movements of these materials across substantial distances (e.g. Granular Rock Fill Replacement and Willow Poles), it was found that transportation accounts for more than half of the total impact.

6 Summary and Recommendations

A number of trials and one practical application of the planting of live willow poles have been examined in terms of their potential to enhance the stability of shallow failures. Each of the sites was inspected in early-2017.

Monitoring of the trials was generally conducted for two to three years post-installation and revealed that in general terms the trials were a success demonstrating that the planting of live willow poles had promoted changes in the soil mass consistent with increased stability. This was broadly confirmed by the site visits conducted in early-2017. However, it was noted that the trials lacked any form of direct monitoring of slope movement or deformation. This would have been helpful, particularly if pre-installation monitoring had also been conducted but it seems that the programme for the trials did not allow for this. This was undertaken at the M6 South of J40 site, planted some 15 years after the trial sites, and has slowed or arrested further movement, at least in the short-term. Continued monitoring is required in order to assess the effects of the willow poles over a period that is meaningful in terms of slope instability.

Lessons learnt/recommendations from the trials and the M6 slope remediation scheme have been detailed. General issues apply whether the trial is of willow poles or of other innovative methods or techniques and include:

- ensuring that the purpose and limitations of a trial are clearly set-out,
- the need to continue the monitoring for a period longer than two to three years in order to fully evaluate the success or otherwise of the trial,
- the need for continuity of purpose before, during and after a trial potentially by the use of a specific team that is not involved in the day-to-day management of the network,
- the need to monitor parameters that directly indicate the stability of the slope or otherwise, and
- the need to ensure that the location of and access to the trials are clearly and accurately recorded and updated in the light of any subsequent changes.

Specific challenges related to willow pole trials and future use include:

- the selection of appropriate willow species including in the light of climate change and in consultation with statutory bodies and appropriate professionals,
- construction issues related to the installation of the poles and the fitment of appropriate tree guards,
- design and construction costs,
- the types of monitoring that have proven to be useful,
- maintenance issues, particularly the need to ensure that the willows are appropriately coppiced and that competing vegetation is eradicated during the period of establishment,
- future uses for willow pole coppicing products, and

-
- the need for a long-term strategy for when willows approach the end of their life to allow for, for example, succession planting.

It is concluded that the planting of live willow poles can be a successful approach to improving the stability of shallow slope failures. All of the evidence suggests that this stability can, with proper maintenance, be applicable in the long-term at sites to which a sixty-year design life is applicable. This has been progressed and design guidance and specification information presented herein.

It was also concluded that innovative techniques such as the planting of Willow Poles can reduce the environmental impact of slope stability measures and the impact on the travelling public. The relatively limited amounts of materials and equipment that are required on site can mean that access to the site can be made off-network, reducing the exposure of road workers, and limiting the need for traffic management, thus limiting delays to the travelling public.

Other opportunities for innovative applications within the field include the option to use willow poles planted at an angle to the vertical such that they act as soil nails, and the use of other vegetative species whether to supply poles or to stabilise the surface of slopes subject to erosion. However, it should be noted that other species are not likely to confer the immediate reinforcement benefit afforded by willow poles unless they too can be configured as poles.

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Appendix A Specification and Design Guidance for the Installation of Live Willow Poles

Specification and Design Guidance for the Installation of Live Willow Poles

Revision 0

Date (October 2018)

Document Owner: Jan Marsden

Document Author: Mike Winter

Content

1. Scope
 2. Principles of design
 3. Site survey
 4. Sourcing of live willow poles
 5. Site preparation
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- Appendix A: Design

Release notes

Version	Date	Details of amendments
Rev. 0	10 2018	The document has been written to make it broadly compliant with the Highways England Future DMRB/MDD drafting rules but is not intended to form part of the DMRB in the immediate future.
Rev. 1		

Foreword

Publishing information

This document is published by Highways England.

Contractual and legal considerations

This is a Highways England document that is intended to be used by the Geotechnical Team and Project Sponsors, and their designers and constructors to specify the installation of live willow poles for stabilising highway slopes. It is written, as far as possible, in the MDD style but does not form part of the DMRB.

Introduction

Background

Shallow slope failure is a widespread and costly maintenance problem that affects highway earthworks, particularly slopes in over-consolidated clays. In most cases the failures occur at depths which are shallower than 1.5m (Ref. 1.1).

Installation of live willow poles offers an easy, relatively rapid and cost effective method of ensuring that vegetation is successfully established both at surface level and at depth within a slope. The live willow poles provide a form of vegetated soil nailing or dowelling which provides immediate improved slope stability and can be used in the prevention, and repair, of shallow slips on highway embankment and cutting slopes. Benefit to the stability of the slope is also gained subsequently over time through establishment of a root system and a reduction in the soil moisture.

A specification for the installation of live willow poles is presented in the main body of this document and a design approach, building on experience gained on a number of trials, is detailed in the Appendix.

Assumptions made in the preparation of the document

The assumptions made in GG 100 *Introduction to the Design Manual for Roads and Bridges* apply to this document.

Acronyms and symbols

Acronym	Definition
Term 2	Definition [Use the tab key for new row]

Symbol	Definition
Term 2	Definition [Use the tab key for new row]

Terms and definitions

Term	Definition
Term 1	Definition [Use the tab key for new row]

1. Scope

Aspects covered

- 1.1. This document covers the principles of design with willow poles, site survey, the sourcing of live willow poles, site preparation, installation, protection of installed poles and maintenance. Further guidance and information, including on design issues, is given in Appendix A and in Ref. 2.I.

Implementation

- 1.2. This Standard shall be implemented forthwith on all schemes involving the use of willow poles to stabilise and/or repair slopes on Highways England's motorway and all-purpose trunk roads according to the implementation requirements of GG 01 "Introduction to the Design Manual for Roads and Bridges".

Health and Safety

- 1.3. Where undertaking any activity that does or may have an impact on safety, either directly or indirectly, for any of the populations on the Overseeing Organisations' motorway and all-purpose trunk roads, risk assessment and management shall be carried out in accordance with the procedures set out by the Overseeing Organisations

Equality and diversity

- 1.4. An assessment as to the applicability of an equality impact assessment (EqIA) shall be carried out.
- 1.5. Where the assessment indicates that an EqIA is needed, an EqIA shall be carried out.
- 1.6. Where the equality impact assessment indicates that people with protected characteristics can be disadvantaged or put at additional risk, solutions to mitigate that risk shall be proposed.

2. Principles of design

- 2.1. DMRB principles, especially those set-out in HD22 (Ref. 1.N), shall be followed.
- 2.2. The location, depth and extent of any shallow failures of the slope and any water bearing strata shall be established.
 - 2.2.1. If the technique is being used as a preventative measure indication(s) of the nature of incipient failure from adjoining areas of slope may be used to inform this process.

NOTE 1 The increased stability of the slope after the willow pole installation will derive primarily from the following:

- 1. The improvement in the resistance to shear on the potential slip surface arising from the enhanced resistance of the total cross-sectional area of the poles which intercept the shear plane.
- 2. The founding of the toes of the poles in more stable strata. For a shallow failure to occur, flow of softened soil between the poles must occur. The spacing between poles is therefore critical in ensuring that arching, rather than flow, is sustained between adjacent poles (Ref. 3.I).
 - a. The maximum shear resistance that each pole can provide to sliding can be calculated as for laterally loaded piles by assuming passive pressures act in the stable soil and active pressures in the failing mass above (e.g. Ref. 4.I and 5.I). The distinction between 'short' and 'long' piles and the shear resistance of the pole section itself also need consideration. In most cases when using willow poles to stabilise slopes against shallow failures, the penetration of the poles beyond the failed zone may be limited and 'short' pile behaviour should be considered assuming the poles are carried through the more stable underlying soil by the sliding layer. 'Long' pile behaviour is relevant to the pole itself yielding in bending or shear.
- 3. The root structure that develops around the live willow pole also increases resistance to shear. This effect is amplified by the increase in effective pole shaft diameter as roots and above ground biomass grow in volume; typically 10% over the initial 3 years after planting.
- 4. The reduced ground water levels and soil moisture through seasonal evapotranspiration due to the growth of willow poles. These effects will be most significant in the summer when hydrological factors are not so critical in terms of slope stability.

NOTE 2 Further advice on design is given in Appendix A and in Ref. 2.I.

- 2.2.2. An alternative design approach, particularly when installing poles at an angle to the vertical is to consider analogies with soil nailing techniques. In this case the live poles act in tension through the development of adherence along the pole. The effectiveness of this will depend on the development of the root growth and the actual live pole inclination angle adopted.
- 2.2.3. Arrays of willow poles may also be used to reduce the development of slope creep due to seasonal swell/shrink cycles in clay.

3. Site survey

General characteristics

- 3.1. The following general characteristics of a potential site shall be recorded:
1. slope details: natural or formed, cutting or embankment;
 2. crest elevation;
 3. slope inclination;
 4. orientation of slope fall line;
 5. geometry: vertical height, width, and slope length;
 6. depth and extent of the shallow failure(s);
 7. location and extent of previous significant repairs;
 8. evidence of any water bearing strata or drainage defect;
 9. existing vegetation cover at the site.
- 3.2. The site for the installation of live willow poles shall be safe for slope working and have well-managed access procedures. Care shall be taken to ensure that working on the site shall poses no significant increase in risk to the safety of users of the network.
- 3.2.1. Slopes selected for the installation of willow poles should normally have an inclination of between 1 (horizontal) in 2 to 3 (vertical) (i.e. a slope angle of generally less than about 30°).
- NOTE 1 Where there is already significant vegetation, the improvement in stability from installing live willow poles is likely to be marginal; open, unshaded slopes are more likely to benefit from willow pole installation.
- 3.3. If significant on-site drainage systems are already installed on the selected slope, the drainage systems shall be accurately located and mapped.
- 3.3.1. If on-slope drainage systems (such as counterforts or herringbone drains) are either present or planned, care should be taken in planting the live willow poles so that the operation of the drains is not impaired.
- 3.3.2. If such drainage is working effectively the need for willow poles should be questioned.
- 3.3.3. If such drainage is not working effectively then further damage from willow pole installation is unlikely to further compromise stability, but repair of the drains should be considered as an alternative option.
- 3.4. Willow poles may not be suitable for sites in or adjacent to designated and protected sites where willows are not found. Design and management in such areas will require approval from Natural England under The Countryside and Rights of Way (CROW) Act 2000 or from the equivalent body and under the equivalent legislation in Scotland, Wales or Northern Ireland.

Soil characterisation

- 3.5. The soils at the site shall be characterised as follows:
1. soil type, colour, structure, and weathering;
 2. particle size distribution;

3. plastic and liquid limits;
4. in-situ moisture profiles;
5. in-situ shear strength;
6. fertility and organic contents.

NOTE 1 Many shallow failures in slopes occur in high plasticity over-consolidated clays where softening has occurred. This softening might have developed because of surface weathering, ground water ingress from a more permeable stratum, or surface water ingress from malfunctioning drainage systems or run-off. In the case of embankments, the clay fill might have been recovered from cuttings and borrow pits and therefore contain high suctions which only gradually dissipate with time causing swelling and softening.

3.5.1. In installations in soft clay consideration should be given to reducing the spacing between poles in order to minimise the potential for flow of the clay between more widely-spaced poles

NOTE 1 Live willow poles have been successfully used to improve slope stability in over-consolidated clays in southern England and in soft clays in northern England.

4. Sourcing of live willow poles

Suppliers

4.1. All cuttings shall be hardwood willow species, sourced from an approved supplier or location.

4.2. Willow cuttings shall be selected from parent plants that are adapted to the local soil conditions on site.

NOTE 1 For example, riverbank types will not survive on exposed dry slopes.

NOTE 2 This is especially important in the context of climate change which is, for example, expected to lead to dry slopes in the south-east of England and the potential for vegetation stress during the summer.

NOTE 3 Willow cannot be grown from seed and so the approach of using live poles requires a ready supply of parent plants.

NOTE 4 The long-term sustainability of the reinforcing provided by the poles is dependent on the survival and establishment of the plants and thus the consequential development of additional rooting structures and root water uptake. If the plants do not survive then the poles themselves will, over a period of time, rot, lose strength and become ineffective in providing reinforcement, and potentially provide a preferential path for water ingress to the slope.

4.3. Specialist advice shall be sought on the selection of appropriate species and potential sources of supply from Highways England's Environmental Advisors and/or a qualified Arboriculturist at an early stage of any proposal to use willow poles as part of a slope repair project.

NOTE 1 The number of species and hybrids of willows is vast.

4.3.1. The individual properties of the available stock should be verified (Ref. 6.I) to ensure that the species is appropriate for the site specific conditions, including in the light of climate change, and stabilisation purposes.

NOTE 1 Three species of willow were trialled in the south of England (Ref. 7.I); these were *Salix alba* (white willow), *Salix spaethii* and *Salix dasyclados*. In the long-term the first two were found to establish and grow successfully while *Salix dasyclados* exhibited a high medium- to long-term failure rate. *Salix viminalis* (or osier, common osier or basket willow) has also been used successfully in the north of England.

NOTE 2 *Salix alba* and *Salix viminalis* are native species. *Salix dasyclados* appears to be native to China and *Salix spaethii* is grown as an energy crop that is coppiced regularly; neither seems to be native to the UK. Advice from Highways England's Environmental Advisors suggests that, whilst they are not precluded from planting non-native species, as part of Government they are committed to plant native tree species other than in exceptional situations. While it may be argued that slope stabilisation is an exceptional situation, the trials demonstrate no advantage to planting with *Salix dasyclados* and that *Salix spaethii* is generally similar in performance to *Salix alba*. Further *Salix spaethii* and *Salix viminalis* are

generally grown for energy cropping and basket production, respectively. Both might therefore require more frequent coppicing.

- NOTE 3 *Salix alba caerulea* is considered to be one of many hybrids of *Salix alba* and *Salix fragilis* and is an exceptionally fast growing variety, which may therefore require more frequent maintenance (trimming and coppicing). However its selection eliminates the potential concerns over the use of *Salix fragilis* close to roads where the shedding of branches may present a problem.

Willow cuttings

- 4.4. All live pole willow cuttings shall be:
1. healthy, free from defects and freshly harvested or brought from cold store;
 2. dormant, i.e. no buds shall have burst before installation;
 3. labelled and kept moist, and protected after delivery on site from frost, heat, wind and damage from impacts.
- 4.5. The dimensions of live willow pole cuttings shall typically be:
1. length: 2.25 to 3.0m;
 2. diameter: butt end: 65 to 90mm, upper end: 40 to 60mm;
 3. shape: straight, or only slightly bent, smoothly tapering or nominally cylindrical, with no bends or branch points forming large bifurcations.
regularity: as the willow poles are to be installed for most of their length into the slope, they shall be free of bumps or angularity (other than small protuberances at branching points) which prevent or hinder entry into the prepared holes.
- 4.6. As a check for acceptable shape, poles shall fit into a 3m long, 125mm internal diameter plastic tube.
- 4.7. The edges of the tube shall be rounded to limit damage to the poles during insertion.
- NOTE 1 The maximum available pole length effectively limits the depth of failure that can be treated using willow poles.

Harvesting

- 4.8. All live willow pole supplies shall be freshly harvested after autumn leaf-fall in a sustainable manner and prepared for direct transportation to site, or taken to an approved cold store.
- NOTE 1 It is preferable in terms of viable propagules that live poles are harvested from the middle third of stems.

Storage and transportation

- 4.9. At all times and locations prior to installation live willow poles shall be wrapped or covered in wet hessian or other fabrics and are kept shaded, cool and moist.
- 4.10. After harvesting, the live poles shall be transported direct to site, or stored in cold store maintained at 1°C until required at the site.

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- 4.11. The live poles shall be transported under tarpaulin cover, wrapped in wet hessian sacking or geotextile and sheltered from the wind and airflow.
 - 4.12. At the site, the live poles shall be stored under water in tanks located in shade, at an ambient temperature not exceeding 12°C.
 - 4.13. Once the holes have been prepared for installation and immediately prior to installation into the slope, small bundles of live poles shall be taken in batches from the site storage tanks, wrapped in wet hessian cloth or similar strong absorbent fabric, and taken directly to the installation location.

5. Site preparation

Site layout

- 5.1. The site shall be set out in full at the start of the works.
 - 5.1.1. A typical layout should comprise a grid of willow pole installation locations at typical spacings of 1m both along and down the slope.
 - 5.1.2. Staggering of the rows of the grid is an option.
- 5.2. The final layout and spacing shall be adjusted by the designer to suit the local site conditions.
- 5.3. In addition to the requirement of stabilising the slope, other factors that shall be considered in determining the layout of the willow poles include the proximity to the carriageway and drainage systems, the locations of underground utilities and lighting and communication cables, adjacent properties, long-term obscuring of traffic signs, and any impact on carriageway lighting.
- 5.4. The spacing of live willow poles shall also be influenced by the access requirements of mechanical plant (e.g. track width,) used in the installation.
- 5.5. The poles shall be installed either near vertically or normal to the slope surface in accordance with the design.
- 5.6. The plant selected to install the willow poles shall be suited to the creation of the holes at the designed inclination (i.e. vertical or normal to the slope surface).

Vegetation

- 5.7. Prior to commencing installation, any existing vegetation which has the potential to provide significant competition for the installed willow poles during the period of early establishment shall be cut back to ground level.
- 5.8. Grass and herb cover shall be removed on non-erodible soils using non-persistent, non-root affecting herbicide.

NOTE 1 Most clays exhibit low levels of erodibility.

Preparation of poles

- 5.9. Prior to installation, the live willow poles shall be prepared in the following manner:
 - 1. the extreme 200 to 250mm length of pole butt ends shall be shaped into a point;
 - 2. the upper end of each pole shall be protected from splitting by wrapping with 2 turns of 1mm diameter galvanised wire 25mm from the end, which shall be secured in position by a minimum of 3 twists.
- 5.9.1. It is good arboricultural practice to enhance nutrient transfer by the use of Mycorrhizal fungi (Ref. 8.I) and this should normally be used. The procedure used for pre-treatment of the poles undertaken at one scheme is described in more detail elsewhere (Ref. 7.I).

6. Installation of live willow poles

Supervision

- 6.1. Live willow poles shall be installed at locations on the slopes to spacings and depths as specified by the designer.
- 6.2. The poles shall be installed following the method detailed in Clauses 6.9 to 6.19.
- 6.3. Live poles shall not be removed from the temporary storage area until at least 6 holes have been prepared.
- 6.4. At no time shall more than 12 holes be prepared in advance of installation.
- 6.5. Each live pole shall be fully-installed into the slope during a single shift.
- 6.6. Live poles shall not be left uninstalled and/or exposed at the end of a shift.
- 6.7. Any uninstalled poles remaining at the end of a shift shall be removed and stored in accordance with the conditions detailed in Clauses 4.9 to 4.12.

Timing

- 6.8. Live willow poles shall be installed after autumn leaf fall and before the beginning of the next growing season, using freshly harvested stock.

NOTE 1 Spring or the beginning of the growing season is recommended as the best time for the propagation of live cuttings (Ref. 9.1). This will typically allow installation between late November and early-April.

Installation

- 6.9. All willow poles shall be inserted in the base of pre-formed holes and driven to bed the pole securely into the base of the hole.
- 6.10. The pre-formed holes shall be at the locations detailed in the site layout plan.
- 6.11. Holes shall be prepared to depths so as to ensure that the requirement of Clause 6.17 is met and that the pole can be driven a minimum of 300mm into the base of the hole
- 6.12. Pre-formed holes of diameters ranging from 75mm to 300mm shall be created to the specified depths using appropriate equipment which may include:
 1. mandrels (i.e. spikes or large-diameter closed or open tubes) driven by manual or mechanical hammer;
 2. hand or powered augers;
 3. machine mounted auger;
 4. window sampling equipment of appropriate diameter.
- 6.12.1. At a site alongside the M6 it was found that 300mm diameter holes were more effective than smaller diameter holes. This allowed for more effective tamping of the fill to the annulus around the pole. Such large diameter holes may be more suitable than smaller diameter holes.

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- 6.13. After completion of the hole, any clay smeared down its sides shall be recovered by light scraping with a grooved scraper in order to improve the interface between the willow poles, the backfill and the surrounding mineral soil.
 - 6.14. In the event that pre-formed holes close up before poles can be inserted and driven, open tubes shall be used to temporarily case the holes.
 - 6.15. Each pole shall be placed butt end first into the base of a pre-formed hole and driven a minimum of 300mm into the slope.
 - 6.16. Driving shall be achieved using sledge and post hammers, or an electric or hydraulic powered impact hammer equipped with a suitable driving tool attachment.
 - 6.17. Each pole shall be driven such that an undamaged length no less than 300mm remains exposed above ground level.
 - 6.18. On completion of driving, the exposed end of each live pole shall be trimmed cleanly at an angle of 60° to the longitudinal axis of the pole. Any splintered portions at the end of the pole shall be cut off cleanly prior to trimming, and the end re-wrapped with wire in accordance with Clause 5.9(1)
 - 6.18.1. In dry or stiff soil, a maximum of 2 litres of fresh water may be added to each hole before or after the installation of the pole.
 - 6.19. After installation the annulus between the pole and its pre-formed hole shall be backfilled with fine dry sand or loam soil to within 250mm of the surface of the slope.
 - 6.20. This final 250mm shall then be backfilled with either the clay arisings removed during the formation of the hole or topsoil.

Records

- 6.21. Records of each installed live willow pole shall be maintained and include the following details:
 1. identification number of the pole;
 2. harvesting date;
 3. location on site;
 4. installation date;
 5. species;
 6. live pole dimensions: length and diameter at each (butt and top) end;
 7. installation details: depth of hole, driven length, whether water added, whether sides of hole needed to be scraped to remove smearing.
- 6.22. Each live willow pole shall be labelled with a durable label detailing its identification number and date of installation.

7. Protection of installed poles

- 7.1. Biodegradable natural fibre (excluding tarred roof felt) tree spats or mats of 450mm minimum diameter shall be placed around each live willow pole after installation and pinned in place in order to provide protection from invasive vegetation.
- 7.2. Tree guards shall be installed to protect live poles from damage during grass cutting operations and, at sites subject to rabbit or other pest infestation, due to interference from animals.
- 7.3. The guards shall be an open polymer mesh type of a minimum 300mm in height and 12mm square mesh.
- 7.4. At sites subject to rabbit or other small pest infestation, the minimum height for the tree guards is 600mm.
- 7.5. The tree guards shall be secured to stakes driven into the ground or by other suitable methods.
- 7.6. Other types of tree guards shall not be used.

NOTE 1 Experience of, for example, continuous, transparent plastic wrap tree guards indicates that these can lead to very humid conditions developing in the annulus between the guard and the pole, which in turn can lead to the development of fungi and/or rot (Ref. 2.1). Ventilation of the above-surface portion of the poles is essential and is fully-addressed by the use of open polymer mesh as described in Clause 7.3.

- 7.7. Fencing shall not be used as an alternative to tree guards.

NOTE 1 The use of fencing to protect an entire site from animal attack is unlikely to be an economic option compared to the use of tree guards. Even if it were to be economically viable, a single breach in a fence can render all of the installed willow poles vulnerable to animal attack.

8. Maintenance requirements

- 8.1. Grass and/or pre-existing vegetation, which has been cut back to ground level prior to installation (see Clauses 5.7 and 5.8) shall be cut and/or trimmed back at least once every year in the first three years after installation.
 - 8.1.1. More frequent grass cutting should be undertaken on the basis of appropriate professional advice as necessary.
 - 8.1.2. After three years the frequency of grass cutting should follow the normal practice for the area.
- 8.2. Coppicing shall be an integral part of any scheme to use willow poles to stabilise a slope.

NOTE 1 Coppicing maintains trees at a 'juvenile' stage of development preventing issues associated with age. For willows such issues include excessive size, and increased brittleness of both branches and trunk.

- 8.3. Regular visual inspections shall be undertaken in order to assess the future need to coppice as well as to assess the health of the plants and therefore the likely success of the scheme.
- 8.4. The need for coppicing, or otherwise, shall be assessed by an appropriately qualified and experienced Arboriculturist.
 - 8.4.1. Annual inspections should be undertaken in the first three to five years after planting with coppicing likely to be needed after five years or longer; it is recognised that this is strongly site dependent.
 - 8.4.2. Coppicing, when required, should be undertaken in three coupes such that one in three plants is coppiced in each of three successive years.
 - 8.4.3. The frequency of inspections and maintenance after the first three to five years should be determined on the basis of arboricultural advice and take full account of the site, the species planted and the development of the plants to date.
- 8.5. Notwithstanding the timings and frequencies of inspection and maintenance activities suggested above, a degree of flexibility shall be built into such activities.
 - 8.5.1. Coppicing, or grass cutting, should not be undertaken simply because the specification suggests that it is necessary.
 - 8.5.2. Coppicing and grass cutting activities should be undertaken on a 'needs' basis and be determined on the basis of appropriate arboricultural advice with the activities fully-integrated in the Landscape Management Plan.
 - 8.5.3. Constructive uses for the coppiced products should be sought. Such constructive uses might include, but are by no means limited to, the following:
 - 1. making the material available to manufacturers of baskets and other woven willow products (withies),
 - 2. the creation of willow brush river bank erosion control mats (e.g. Ref. 10.I),
 - 3. its use as poles for future willow poles slope stabilisation schemes if poles of an appropriate size can be generated, or

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- 4. the creation of fauna habitat on appropriate sites.
 - 8.5.4. The frequency and timing of coppicing may also be influenced by the intended destination of the coppiced products.
 - 8.6. Both the costs of inspections and those associated with coppicing shall be considered in terms of the potential for future willow pole schemes.
 - 8.7. A long-term strategy shall be developed for when willow poles approach the end of their life
- NOTE 1 Such a long-term strategy may include, for example, a scheme for succession planting.

9. Normative references

	Title
Ref. 1.N	DMRB Document HD 22, Managing geotechnical risk.

10. Informative References

	Title
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Appendix A Design

The design findings presented in this section are derived from a trial of willow poles at the M23 near Gatwick (Ref. 2.I and Ref. 7.I), this in turn built upon lessons learnt from earlier trials at the A10, M1 and A5.

A1 Original design

A significant amount of soils data was available from the M23 site investigation (Ref. 11.I), including reviews of reports of earlier investigations. For this reason, more detailed design analyses were undertaken at the M23 site than at the earlier trial sites, although the same design philosophy can be applied elsewhere. Detailed findings and recommendations from these analyses are reported elsewhere (Ref. 12.I).

At this particular site on the M23, there were no tall trees surcharging the site and other site specific factors which were taken into account were as follows:

- toe weakening due to saturation by water stored in the adjacent flood storage lagoon;
- loss of toe support to the slope and the development of slope failure along a plane at shallow depth (~1m).

Assuming that the lower part of the pole is securely founded in the stable zone below 1m depth, the upper portion of the pole is acted upon by the unstable zone. For this particular design, the ultimate lateral capacity of the poles based on frontal passive earth pressure was estimated (Ref. 13.I). The contribution due to lateral shear drag was also considered.

For the purpose of the analyses a spreadsheet was developed based on conventional infinite slope theory with incorporation of the dowelling effects of the presence of arrays of live willow poles. In these calculations, the factors of safety (F) against sliding are expressed in the customary manner and represent the ratio of the shear strength along the yield surface divided by the disturbing shear forces on that plane. The full formula, which employs effective stress strength parameters, takes account of the pore water pressure at the yield surface, and also surcharge and wind loading on trees (Ref. 14.I), as follows:

$$F = \frac{\{(c' + c'_R)l + [(W + S_W) \cos \beta - u \cdot l] \tan \varphi'\}}{\{(W + S_W) \sin \beta + D\}}$$

Where

β is the slope inclination,

u is the pore water pressure at slip surface,

l is the length of the failure surface,

c' is the effective cohesion,

c'_R is the increase in cohesion due to root reinforcement,

φ' is the angle of internal friction of the soil,

S_w is the weight of surcharge from vegetation (if any), and

D is the downslope wind force on trees (if appropriate).

The development of sufficient live pole resistance to improve the factor of safety relies on an adequately embedded section into the stable zone below the shear zone. This was assumed in the design (Ref. 13.I).

Factored values of 1,000 and 1,600kN/m² were used for the ultimate shear stress of the willow poles and these were derived from the ultimate shear stress of 4,800kN/m² for the wood (Ref. 15.I). For the purpose of the analyses, an effective cohesion (c') of zero and a soil friction angle (ϕ') of 24° were assumed for the clay fill of the embankment which had a slope angle of 24° and a slope height of 3.5m. On this basis, the calculated factors of safety against sliding for different pole spacings are given in Table A1.1 and Table A1.2 for permissible willow pole shear stresses of 1,000 and 1,600kN/m² respectively.

Table A1.1 Factors of safety against sliding for permissible willow pole shear stresses of 1,000kN/m².

Factors of Safety					
Across slope spacing, y (m)					
Downslope spacing, x (m)	0.5	0.75	1.0	1.25	No enhancement
0.5	1.75	1.50	1.37	1.29	
0.75	1.50	1.33	1.24	1.19	
1.0	1.37	1.24	1.18	1.14	
1.25	1.29	1.19	1.14	1.11	
					1.0
Average pole diameters (mm)				Top: 50	Bottom: 77.5
Permissible willow pole shear stress				1,000kN/m ²	
Water table depth below slope surface				1m	

Table A1.2 Factors of safety against sliding for permissible willow pole shear stresses of 1,600kN/m².

Factors of Safety					
Across slope spacing, y (m)					
Downslope spacing, x (m)	0.5	0.75	1.0	1.25	No enhancement
0.5	2.21	1.80	1.60	1.48	
0.75	1.80	1.53	1.40	1.31	
1.0	1.60	1.40	1.29	1.23	
1.25	1.48	1.31	1.23	1.18	
					1.0
Average pole diameters (mm)				Top: 50	Bottom: 77.5
Permissible willow pole shear stress				1,600kN/m ²	
Water table depth below slope surface				1m	

A2 Back analysis after establishment of willows

Three aspects of enhanced stabilisation due to the willow poles establishing themselves on the slopes were considered for inclusion into a modified slope stability analysis:

- i. Increased shear resistance due to increased diameter of live pole. Observations of growth at the M23 site were primarily based on measurements during exhumation of randomly selected willow poles. These indicated increases of pole diameter of between 10 to 20%.
- ii. Increased shear resistance due to post-installation root growth. Only a limited qualitative evaluation of root growth was possible from examination of the exhumed live willow poles. In the absence of this data, the lengths of the poles were divided into three depth zones and appropriate root area ratios (A_r/A) assigned to these zones. The contribution of roots to the increase in soil shear strength is given by:

$$\Delta S = T_r \left(\frac{A_r}{A} \right) (\sin \theta + \cos \theta \tan \phi)$$

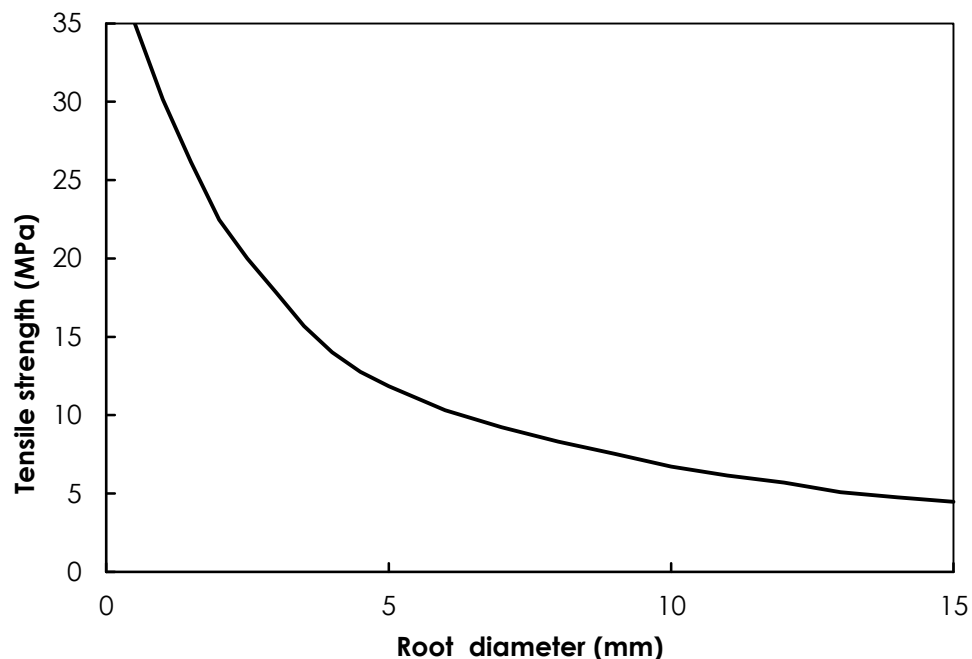
Where

θ is the angle of shear distortion, and

T_r is the tensile strength of the root.

The relation between root diameter and tensile strength shown in Figure A2.1 has been used to provide lower bound values which can be compared with values presented in the literature (Ref. 16.I).

Figure A2.1 Relation between tensile strength and root diameter



A value of 2% was considered to be the greatest root area ratio likely to be encountered in practice.

A range of root sizes and lengths were recorded at the M23 site based on the live willow pole exhumations. The range of root sizes adopted in the slope stability analyses was 1 to 5mm.

- iii. Increased shear resistance due to increased soil suctions caused by plant evapo-transpiration. Measurements at the M23 site confirm that a reduction in subsurface soil moisture content and in pore water pressure both occur within the slope during the growth season of the willow poles. However, during the winter dormancy period, it is unlikely that these changes are sustained and for this reason this effect has not been included in the back-analysis of slope stability.

A summary of the results from the slope stability calculations is given in Table A2.1. This table includes the original design data and the back-analyses assuming two different pole shear strengths and various root area ratios.

For pole shear strength of $1,000\text{kN/m}^2$, an increase in pole diameter by 10% alone increases the factor of safety at the vulnerable depth of 1m to 1.23 from 1.19. A pole diameter increase of 20% further improves the apparent factor of safety to 1.27. The presence of roots increases the factor of safety to 1.36 for root area ratios of 0.15%, 0.10% and 0.05% in the upper, middle and lower third lengths of live pole respectively.

Table A2.1 Summary of results of slope stability analyses.

Live pole spacing along slope (m)	Live pole spacing down slope (m)	Pole shear strength (kN/m ²)	Diameter of pole (mm)		Root area ratios (%)			Factor of safety at 1m depth
			Tip	Butt	Upper third	Mid third	Lower third	
0.5*	1.25*	1,000	80	78	-	-	-	1.29
1.0 ⁺	0.75 ⁺	1,000	51	61	-	-	-	1.19
			56	67	-	-	-	1.23
			61	73	-	-	-	1.27
			56	67	0.15	0.10	0.05	1.32
			61	73	0.15	0.10	0.05	1.36
			61	73	0.50	0.25	0.15	1.49
1.0 ⁺	0.75 ⁺	1,600	56	67	0.15	0.10	0.05	1.45
			61	73	0.15	0.10	0.05	1.52
			61	43	0.50	0.5	0.15	1.65
			61	73	0.50	0.25	0.15	1.51
			56	67	0.50	0.25	0.15	1.43

* Original design

⁺ As installed spacings

Further improvement up to a factor of 1.49 occurs if root area ratios of 0.5%, 0.25% and 0.15% respectively are considered.

Further analyses for pole shear strengths of 1,600kN/m², show similar trends in improvement of factors of safety as enhanced growth of the live willow poles occurs.

A3 Typical costs

Live willow costs are dependent on the particular characteristics and requirements of the intended site. These will include slope geometry, pole spacing, ground conditions and ease of access for mechanical plant.

However, the installations carried out as part of this project give some typical costs for the technique in 2000 and 2001. It is possible that some reduction in costs may be possible as the work was carried out with a high standard of supervision using experienced staff.

In general the installations fell into three broad categories, characterised by rate of installation. This information is presented in Table A3.1. It can be seen that primary cost categories are drilling, labour and pole supply costs. As design costs are only available for the M23 Gatwick installation these have not been included in the table. However at the M23 site these costs amounted to between £8k and £10k. It is also conceivable that the extra costs for a design encompassing a longer stretch of embankment would not have been significantly higher.

Therefore in broad terms, the cost of the technique in 2000 and 2001 per installed pole varied between £50 and £87. The variation was attributed to the method of drilling and the ease of access for suitable plant. These costs correspond to £90 to £155 per pole at 2017 prices (Ref. 2.I).

Table A3.1 Typical installed costs for the live willow pole technique (at 2000/01 prices).

	Pole installation rate per week (approximate)		
	80	100	300
Typical installation method	Handheld power auger		Machine mounted auger
Access level required	Pedestrian	Pedestrian	Vehicular to slope toe/crest
Typical material	Stiff clay	Soft clay	Stiff clay
	Approximate costs per pole (£)		
Live willow poles	11	11	9
Pole protection	2	2	2
Topsoil	2	2	1
Drilling	33	26	10
Labour (setting out, pole preparation, etc.)	35	25	25
Project management	4	3	3
Approximate installed cost per pole	87	69	50

Work to evaluate the effectiveness of innovative geotechnical repair techniques for slopes has been commissioned by Highways England. The techniques are the planting of live willow poles, fibre reinforced soil and electrokinetic geosynthetics. These techniques were used in place of conventional approaches to repair in order to reduce the overall impact of various challenges including environmental constraints (habitat and visual), access and utility constraints, and to address the need to reduce the scale and/or cost of traffic management and traffic delays. Trials of the techniques have been undertaken over the preceding 20 years or so but monitoring was generally limited to just a few years post-construction. Longer term evaluation has not generally been undertaken. This report presents an assessment of the effectiveness of live willow poles as an aid to increased stability and is one of a series for this project.

Other titles from this subject area

- PPR 873** Innovative geotechnical repair techniques: effectiveness of fibre reinforced soil. R Seddon, M G Winter & I M Nettleton. 2018
- PPR 890** Innovative geotechnical repair techniques: effectiveness of electrokinetic geosynthetics. I M Nettleton, R Seddon & M G Winter. 2018
- PPR 889** Innovative geotechnical repair techniques: comparative life cycle assessment. D Leal, M G Winter, R Seddon & I M Nettleton. 2018
- PPR 891** Innovative geotechnical repair techniques: recommendations and guidance for management of future Highways England trials with innovative techniques. M G Winter, I M Nettleton & R Seddon. 2018

TRL

Crowthorne House, Nine Mile Ride,
Wokingham, Berkshire, RG40 3GA,
United Kingdom
T: +44 (0) 1344 773131
F: +44 (0) 1344 770356
E: enquiries@trl.co.uk
W: www.trl.co.uk

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