THE FUTURE OF TRANSPORT

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## Innovative Geotechnical Repair Techniques

### Comparative Life Cycle Assessment

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## Executive Summary

This report provides estimates of the carbon impacts of four remedial techniques used to stabilise a notional 25$^{o}$ highway slope 10m high and 100m wide for failure depths of 1m and 2.5m. The four techniques are Granular Rock Fill Replacement, which was used as a control), Willow Pole planting, Fibre Reinforced Soil (FRS), and Electrokinetic Geosynthetics (EKG). These were compared using a cradle-to-site life cycle assessment. Five life cycle steps were defined and assessed, from the acquisition and processing of each installation's constituent materials, through to the construction of the final product – a stabilised slope.

A cradle-to-site Life Cycle Assessment (LCA) boundary was adopted (using the cut-off approach), as opposed to a full cradle-to-grave assessment. This approach was adopted for a number of reasons. Firstly, each of the techniques has different maintenance requirements, occurring in uneven time frames. Secondly, the expected lifetimes and end-of-life scenarios for each technique vary in ways that would not allow for a balanced comparison within equal time frames. Data was compiled from a number of representative sources and where possible was selected for UK specific values. Transport was calculated using tonne.km factors for a range of delivery vehicles, depending on the material and scenario. All transport was calculated for two-way (full outward-empty return) journeys.

This study aimed to provide a range of general estimates, and as the slope under assessment was hypothetical, it did not have a real-world location. As a consequence, the transport impact calculations are based on assumed low-medium-high distances for transport impact calculations. The functional unit of analysis of the assessment was the ability of each technique to stabilise 1m$^2$ of failed slope.

It was found that at both failure depths, and for all transport cases, the greatest environmental impact was for the Granular Rock Fill Replacement. At 1m and 2.5m failure depths this technique resulted in an impact of 51 to 174 kg$CO_2$e/m$^2$ of failed slope respectively, depending upon the transport distance assumed. Willow Poles had the least impact, resulting in 4 to 12 kg$CO_2$e/m$^2$ of failed slope respectively. For the 2.5m failure depth EKG was the second best performing technique (EKG was not assessed for the 1m failure depth scenario), with an impact of around 14 kg$CO_2$e/m$^2$. FRS had an impact ranging between 16 and 35 kg$CO_2$e/m$^2$. 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.

# 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 (Winter et al. 2018), Fibre Reinforced Soil (FRS) (Seddon et al. 2018) and Electrokinetic Geosynthetics (EKG) (Nettleton et al. 2018) and 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.

This report describes the comparative life cycle assessment (LCA) study undertaken as part of the project. The environmental benefits and burdens of one conventional (control) and three innovative repair techniques are examined:

- Granular Rock Fill Replacement (control).
- Willow Poles.
- Fibre Reinforced Soil (FRS).
- Electrokinetic Geosynthetics (EKG).

In addition the parameters that have a significant impact on the environmental performance of each technique are identified.

## 2 Background

The functional unit used for the investigation is the ability of each technique to stabilise 1m$^2$ of failed slope. This functional unit was chosen to allow the quantity of materials to be related to its use. In this study two slopes of identical dimensions were assessed; however the imminent failure depth, requiring the application of the above remedial techniques, between the two differed. The assessment was carried out for a shallow slope failure (to a depth of 1m below the surface) and a deep failure (to a depth of 2.5m below the surface). The assessment was not carried out for EKG in the 1m failure depth scenario as this technique is not considered suitable for such shallow failures. For each failure depth the slope dimensions are identical, with a vertical height of 10m, a horizontal width of 100m, with the slope at an inclination of 25$^o$.

In this study only a partial life cycle of each technique was considered: cradle-to-site (installation). The system investigated is presented in Figure 1. A cradle-to-site boundary was set, as opposed to a cradle-to-grave boundary, as each of the four techniques have differing maintenance interventions and end-of-life scenarios even though the earthworks design life would notionally be for 60 years. With these factors in mind a fair comparison could only be undertaken in a cradle-to-site context, from material extraction and production to the installation of each technique. While a vast range of environmental impacts are available for consideration, under a number of supporting methodologies, this study is solely focused on the climate change impacts generated in terms of global warming potential across a time horizon of 100 years (GWP100), expressed in kg of carbon dioxide equivalents (kg$CO_2$e). The LCA is modelled using a cut-off approach. The basic premise of this approach is that the primary production of materials is always allocated to the primary user of that material. If a material is recycled, the primary producer does not receive any credit for the provision of recyclable.

**Stage 1** — **Raw/Recycled Material Acquisition & Processing**

- Acquiring raw materials from the natural environment; materials from secondary sources (e.g. recycled steel). Subsequent processing/manufacturing to transform these materials into a product(s) prior to use

**Stage 2** — **Transport of Materials to a Temporary Site**

- Transport of materials to point of use

**Stage 3** — **Construction Enabling Works**

- Excavation and removal of failed material
- Site clearance (vegetation)

**Stage 4** — **Transport of Materials to Site**

- Transport of materials to point of use

**Stage 5** — **Installation**

- Placing and installing materials at the construction site

**Figure 1: Overview of life cycle stages**

The availability of existing representative data relating to the materials and construction processes of these four techniques proved difficult to obtain. As such all data is sourced from secondary sources and in some cases had to be adapted, under stated assumptions, for its inclusion in the analysis, i.e. life cycle inventory (LCI) data for the production of Willow Poles of the same specification as those used in the technique was not available, as a consequence the results from a limited amount of existing Willow Pole LCI studies had to be modified and scaled to provide the data in the required format. The default data sources for materials, processes, and transport were selected from the EcoInvent Database version 3.3 (EcoInvent 2016a to 2016h), Institution of Civil Engineers (ICE) Embodied Energy and Carbon Database (Circular Economy 2011), the ICE CESMM3 Carbon & Price Book (ICE 2011), and the DEFRA Greenhouse Gas (GHG) Emissions Factors Database (DEFRA 2016). Where possible UK specific data was used, however for certain datasets, UK specific values were not available, in which case, European and Globally harmonised datasets were adopted. In cases where inventories were not available, these were constructed using figures from literature, case studies and manufacturers.

# 3 LCA Scenarios

In this study seven cradle-to-site scenarios were assessed for the repair techniques and failure depths set-out in Table 1, EKG is only assessed for a slope failure depth of 2.5m as this method is not considered to be suited to shallow failure depths. The Granular Rock Fill Replacement scenarios for both failure depths are used as the control case for the point of comparison with the other techniques as this is the most conventional technique for the repair of unstable slopes. It must be noted that the slope under examination has no real-world location; essentially the site could be located anywhere in England. As a consequence each scenario is assessed for low, medium and high transport distances. Further to this it should also be noted that the only difference between scenarios n.1 & n.2 is the volume of slope that is treated, and as such the quantity of materials required. The individual processing stages for each scenario remain the same. The following section provides an outline of these scenarios.

**Table 1: LCA scenarios**

| Scenario Reference | Technique | Failure Depth (m) | Volume of Failed Material ($m^3$) |
|---|---|---|---|
| **A.1** | Granular Rock Fill Replacement (Control) | 1 | 2,038 |
| **A.2** | Granular Rock Fill Replacement (Control) | 2.5 | 4,692 |
| **B.1** | Willow Poles | 1 | 2,038 |
| **B.2** | Willow Poles | 2.5 | 4,692 |
| **C.1** | Fibre Reinforced Soil (FRS) | 1 | 2,038 |
| **C.2** | Fibre Reinforced Soil (FRS) | 2.5 | 4,692 |
| **D.2** | Electrokinetic Geosynthetics (EKG) | 2.5 | 4,692 |

## 3.1 Scenarios A.1 and A.2: Granular Rock Fill Replacement (Control)

Scenario A explores the environmental performance, in terms of $kgCO_2e$, of Granular Rock Fill Replacement used to repair $1m^2$ of a slope with failure depths of 1m and 2.5m

### *3.1.1 Stage 1: Raw/Recycled Material Acquisition and Processing*

The Granular Rock Fill Replacement is a very simple technique and only requires the production of two primary materials: 80 to 100mm coarse granular fill (akin to SHW Series 600 Class 6G) and Terram 4000 Geotextile, or similar, which is placed at the base of the granular fill. The coarse aggregate production includes the following processes: quarrying (open pit mining by drilling, blasting and excavation) conveying, crushing, grading (vibratory screens and mills), washing, and stockpiling. The geotextile production processes include: extraction/refinement of crude oil, production of polypropylene/polyethylene fibres, and production of geotextile (includes intermediate transport stages).

### 3.1.2 Stage 2: Transport of Materials to a Temporary Site

This transport stage models the two-way return journey for each material: i.e. a fully loaded truck transports the materials the defined distance, unloads, and then makes the return journey back to its origin carrying no load. The environmental performance and efficiency of each mode is based on average global values for vehicles of that particular class. Global values, expressed in tonne.km, have been taken from EcoInvent (2016a to 2016h).

All transport is powered through diesel combustion, which reflects situation in the UK. It is assumed that all transport, in every scenario, is EURO4 emissions class. EURO4 was selected since in 2014 the average age of light and heavy duty vehicle fleet operating in Europe was eight years old. As these vehicles would have been produced after 2006 they would have been designed to meet EURO4 emissions standards. As discussed earlier, this study addresses a hypothetical site which could be located anywhere in England as such distances have been assumed for low, medium and high cases (see Table 2).

In the case of transporting aggregates; the medium case was based on the findings from a Mineral Products Association (2011) study which concluded that the average delivery distance for aggregates used in the UK highways sector was 52km. Aggregates used in highway construction products are typically sourced locally so as to minimise the costs incurred when transporting large quantities. For this reason it was concluded that it would not be feasible for aggregates to travel substantially larger distances than the above, as such it was estimated that the low and high transport cases would only differ from the average by ±15km.

Geotextiles are widely available across the UK, as such it was assumed that their delivery distance would not be dissimilar to that of the coarse granular fill. It is assumed that all materials are transported from their point of production/distribution to a temporary site (located 0.5km away from the construction site) where they are stockpiled until they are required on-site.

**Table 2: Scenario A transport distances**

| Material | Mode | Low (km) | Medium (km) | High (km) |
|---|---|---|---|---|
| Coarse Granular Fill | Freight Lorry (GLO) (EURO4)<br>16-32 tonne (GVW)<br>20 tonne payload | 37 | 52 | 77 |
| Geotextile | Freight Lorry (GLO) (EURO4)<br>7.5-16 tonne (GVW)<br>10 tonne payload | 33 | 66 | 100 |

### 3.1.3 Stage 3: Construction Enabling Works

This stage includes site activities that must be undertaken in order for construction to begin. For Granular Replacement the following processes have been included: clearing the site of surface vegetation (small trees and shrubs), excavation of failed material (for a typical motorway cutting), cutting benches (0.5m x 1m) into the underlying slope, and transporting the waste material to a disposal facility. The transport step within this stage follows the same assumptions as highlighted in Section 3.1.2. The mode is a freight lorry (GLO) (EURO4) 16 to 32 tonne (GVW) 20 tonne payload. The location of the disposal facility is presented as a low, medium, high range (15km, 30km, 45km respectively). For both failure types/depths the mass of failed soil removed from site is substantial, as such distances were assumed to be relatively low as the contractor would look to minimise disposal costs. This stage does not account for any temporary retaining structures as these materials would be used for multiple projects, as such assigning a proportion of this impact was outside of the scope of assessment

### *3.1.4 Stage 4: Transport of Materials to Site*

As discussed above, materials were initially transported to a temporary stockpile site, located 0.5km from the main construction site. The same assumptions are made in this stage as in Stage 2 (see Section 3.1.2).

### *3.1.5 Stage 5: Installation*

The final stage considered was the installation of materials. For geotextiles the construction processes included laying and securing the fabric in place on top of the cut benches. Once the geotextiles are laid the coarse granular fill is placed. This requires the following processes, which have been accounted for: filling, spreading and levelling.

## 3.2 Scenarios B.1 and B.2: Willow Poles

Scenario B explores the environmental performance, in term of kg$CO_2$e, of live Willow Poles used to repair 1$m^2$ of a slope with failure depths of 1m and 2.5m.

### *3.2.1 Stage 1: Raw/Recycled Material Acquisition & Processing*

The materials required for this slope stabilisation technique are willow stem cuttings, geogrid reinforcement, and topsoil. The production of willow stems accounts for the following processes and inputs: soil cultivation, seed sowing/planting, fertilisation (mineral fertilisers), weed control (pesticides), agricultural plant movements, harvesting, transport of stem cuttings from field to farm, and storing the willow cuttings in a cold storage house.

For willow production UK specific values were not available and as such values have been obtained for willow production in Germany. For a 1m failure depth Willow Poles were 2m in length, for a 2.5m failure depth the Willow Poles were 3.5m in length. The production of geogrid material includes the direct burdens of raw material (plastic) production, additives, working materials (such as water, lubricating oil) and the energy (electricity and thermal energy), production infrastructure and plant, waste water treatment and disposal of waste.

### *3.2.2 Stage 2: Transport of Materials to a Temporary Site*

For this technique it is assumed that there is no temporary stockpiling site, see Section 3.2.4.

### *3.2.3 Stage 3: Construction Enabling Works*

The processes accounted for in this life cycle stage are as follows: site clearing (removing vegetation, as required for site access, such as small trees and small shrubs) and auguring 300mm diameter holes (1.7m and 3.2m deep for failure depths 1m and 2.5m respectively); as 300mm of the poles remain protruding from the ground after installation the poles are therefore a total of 2m and 3.5m long respectively. All construction activities are diesel powered unless stated otherwise. A proportion of the soil removed is retained for later use; however the majority of this material is transported to a disposal facility; for distances and transport mode, see Section 3.1.3). It must be noted that this stage may occur prior to the delivery of materials to site.

### *3.2.4 Stage 4: Transport of Materials to Site*

The basic assumptions, with regards to transport distance and journey type, in this stage are the same as those stated in Section 3.1.2.

Willow Poles are transported via a refrigerated lorry from the point of storage to site. In this scenario there is no temporary site storage, as once the willow is delivered it must be planted as soon as possible to avoid spoiling, no provision for cold storage on-site has been allocated as the mass of poles required is relatively small compared to that of primary materials required in other scenarios. As can be seen from Table 3 two different types of vehicle are used to transport the Willow Poles: a 3.5 to 7.5 tonne refrigerated lorry and a 7.5 to 16 tonne refrigerated lorry. In scenario B.1 and B.2 approximately 4.6 tonnes and 16.3 tonnes of Willow Poles are required respectively. The 3.5m poles have undergone more growing seasons than the 2m poles. As such the diameter of the 3.5m pole is greater than that of the 2m pole, coupled with the increase in length this results in almost four times the mass being transported for scenario B.2. With regards to willow transport distances there were no previous studies which provide an estimate of average willow delivery distance. With this in mind hypothetical distances were used, as seen in Table 3. Willow production is common in the UK however willow plantations are sparsely located around the country. In this case potential delivery distances were assumed to be much further than that of other materials.

Geogrid is a readily available material and is widely stocked throughout the UK, as such the transport distances are assumed to be relatively small. Similarly topsoil is widely available throughout the UK, and it was assumed that this would be sourced locally (see Table 3).

### *3.2.5 Stage 5: Installation*

Once the site has been cleared the Willow Poles are placed in the pre-augured holes. Topsoil is then used to fill the holes up to 0.25m below the surface level. Topsoil is loosely compacted. The remaining 0.25m is filled and sealed with site-won Class 2 material. 25mm aperture geogrid is then wrapped around each pole top which extrudes 0.3m above ground level.

**Table 3: Scenario B transport distances**

| Material | Mode | Low (km) | Medium (km) | High (km) |
|---|---|---|---|---|
| **Willow Poles (for 1m failure depth)** | Freight Lorry with Refrigeration Unit (GLO) (EURO4)<br>3.5-7.5 tonne (GVW)<br>3 tonne payload | 100 | 200 | 300 |
| **Willow Poles (for 2.5m failure depth)** | Freight Lorry with Refrigeration Unit (GLO) (EURO4)<br>7.5-16 tonne (GVW)<br>10 tonne payload | 100 | 200 | 300 |
| **Geogrid Textile** | Freight Lorry (GLO) (EURO4)<br>3.5-7.5 tonne (GVW)<br>3 tonne payload | 25 | 50 | 75 |
| **Topsoil** | Freight Lorry (GLO) (EURO4)<br>16-32 tonne (GVW)<br>20 tonne payload | 25 | 50 | 75 |

## 3.3 Scenarios C.1 and C.2: Fibre Reinforced Soil

Scenario C explores the environmental performance, in term of $kgCO_2e$, of FRS used to repair $1m^2$ of a slope with failure depths of 1m and 2.5m.

### *3.3.1 Stage 1: Raw/Recycled Material Acquisition & Processing*

This stabilisation technique only requires two materials, polypropylene fibre strips (approximately 2mm x 50mm) and the failed soil mass from the site. Production of the polypropylene fibre strips accounts for all processing steps necessary to produce polypropylene film and a subsequent processing step of shredding the film into strips of the dimensions stated above. Production and shredding is assumed to be undertaken in the same production facility.

### *3.3.2 Stage 2: Transport of Materials to a Temporary Site*

As with previous scenarios there are no existing studies which note the average delivery distance of polypropylene strips for use in construction projects. As such a range of delivery distances were assumed. For the low, medium and high transport cases these distances were assumed to be 100km, 150km and 200km respectively. This assumes that FRS can, in future, be sourced in the UK; at present the materials are sourced from the USA in the absence of a UK-based manufacturer and supplier. This change in the supply-chain would almost certainly be a prerequisite for the use of FRS to become commonplace in the UK. Polypropylene strips were assumed to be transported via freight lorry, 16 to 32 tonne (GVW), with a 20 tonne payload (EURO4) (GLO). It should be noted that this assessment does not account for the transportation of plant used on site.

#### *3.3.3 Stage 3: Construction Enabling Works*

The following processes have been accounted for: site clearing (removing vegetation such as small trees and shrubs); excavation of failed material, transporting excavated material to a temporary site located 0.5km away from the main site, mixing the failed soil mass with the polypropylene strips using stabilised soil batch mixing plant. The excavated material was transported from the main site to the temporary site via truck, 16-32 tonne (GVW), with a 20 tonne payload (EURO4) (GLO). Note all plant and transport is diesel powered.

It is accepted that the 0.5km distance may be less on some sites but is considered to be a reasonable estimate for a typical site. Indeed, further carbon savings may be available if the FRS process could be configured such that mix-in-place techniques could be used.

#### *3.3.4 Stage 4: Transport of Materials to Site*

Once the soil has been mixed with the polypropylene strips it is transported back to the main site, 0.5km away, via a freight lorry, 16 to 32 tonne (GVW), with a 20 tonne payload (EURO4) (GLO).

#### *3.3.5 Stage 5: Installation*

The processes included in this stage are filling, spreading, levelling and compacting; all plant is diesel powered.

### 3.4 Scenarios D.1 and D.2: EKG

Scenario D explores the environmental performance, in term of kg$CO_2$e, of live Willow Poles used to repair 1$m^2$ of a slope with failure depths of 1m only as the technique is not overly suited to such shallow failures.

It must be noted that this novel technique is provided by a small number of specialist contractors; as such the data for manufacture and assembly techniques was not easily attainable.

However, the constituent materials used to assemble the anodes and cathodes were known, alongside the other materials required in the design of this technique. With these two factors in mind it was possible to define the quantities of materials required for the installation. However no data was available from the contractors with regards to their supply chain and manufacturing processes, as such no allowance has been made for the transport of constituent materials from their point of production to the point of assembly and manufacture. Further to this no allowance has been made for the energy and subsequent emissions deriving from the assembly of the constituent materials into the final product. There are a number of existing case studies available, containing limited data, from contractors, which have been used cautiously to guide the calculations with regards to construction techniques, design, quantities, and energy consumption of this technique (Balfour Beatty and Mott MacDonald 2014.).

### 3.4.1 Stage 1: Raw/Recycled Material Acquisition & Processing

Compared with the previous techniques this approach makes use of a large number of different materials. The anodes are made from sections of perforated steel 42.5mm diameter tube, connected via threaded couplings. Each anode is assembled on-site to a length of 7m. A vertical spacing of 2.5m and a horizontal spacing of 3m has been assumed for the anodes, the anodes require centralisers, assumed to be made of steel, every 1.5m. A 7m long, 16mm diameter steel reinforcement bar inserted inside each anode, and grouted in place using Conbextra HF. A 300mm by 300mm by 6mm galvanised steel face plate is connected to the end of the threaded rebar and secured.

The cathodes are made from 6m long UPVC tubing, 60mm diameter, wrapped with a thin geosynthetic mesh, geosynthetic filter fabric and an outer conducting stainless steel woven sock. The system is connected via cabling to a DC panel and AC generator, transformer and diesel storage tank.

### 3.4.2 Stage 2: Transport of Materials to a Temporary Site

Transport for all anode, cathode and set-up equipment (with the exception of the generator, transformer, and fuel tank) is assumed to travel from a single distribution point together. Table 4 provides transport modes and hypothetical distances for low, medium and high cases. The same assumptions, as used for the previous techniques, have been applied for this case.

### 3.4.3 Stage 3: Construction Enabling Works

Preparation works are minimal for this technique. The site must be cleared of undergrowth and holes are augured for the cathodes. Note that some sites have been constructed without removing trees, only surface vegetation. However, this means that the spacing of both the anodes and the cathodes are variable and that the total number used is also variable. The assessment of such a relatively complex scenario is beyond the scope of this present work.

### 3.4.4 Stage 4: Transport of Materials to Site

All materials are taken in loads from the temporary stockpiling site to the main site a distance of 0.5km away, via a freight lorry, 16 to 32 tonne (GVW), with a 20 tonne payload (EURO4) (GLO).

### 3.4.5 Stage 5: Installation

The cathodes are inserted into their augured holes, and the anodes are assembled and driven into the ground using a slope climbing rig. Anodes and cathodes are connected to the electrical equipment. To complete the installation power is supplied via the generator and transformer for 42 days at a rate of 22.1MJ/m$^3$ of failed material. All installation plant is assumed to be powered by diesel combustion.

**Table 4: Scenario D transport distances**

| Material | Mode | Low (km) | Medium (km) | High (km) |
|---|---|---|---|---|
| Anodes, cathodes, wiring | Freight Lorry (GLO) (EURO4)<br>7.5-16 tonne (GVW)<br>10 tonne payload | 150 | 300 | 450 |
| Generator, transformer, fuel and storage tanker | Freight Lorry (GLO) (EURO4)<br>3.5-7.5 tonne (GVW)<br>3 tonne payload | 25 | 50 | 75 |

# 4 Results and Discussion

Table 5 below presents the cradle-to-site total and areal environmental impact of each of the four approaches explored. It can be seen that for the shallow failure (1m depth, D1) the lowest environmental impact technique is the installation of live Willow Poles, with a total impact of 8.8 to 13.1 $TCO_2e$ and an impact of 3.7 to 5.5 $kgCO_2e/m^2$ of treated slope, from low to high transport cases. The highest environmental impact technique for a shallow failure is the control, Granular Rock Fill Replacement, with a total impact ranging from 120.1 to 89.3 $TCO_2e$. This represents an impact of 50.7 to 80 $kgCO_2e/m^2$, depending on the transport case. FRS has a total impact of 36.4 to 36.6 TCO2e, representing an impact of 15.4 to 15.5 $kgCO_2e/m^2$. As discussed earlier EKG is not applicable for shallow failures. If the impact of the Granular Rock Fill Replacement is set as 100%, the relative impact of the Willow Pole technique is 6.7 to 7.3% and that of FRS is 19 to 30%. These results are also illustrated in Figures 2 and 3.

**Table 5: Overall results**

| **Method** | **Range** | **Total Impact (Tonnes of $CO_2$eq.)** | | **Areal Impact of Treated Soil ($kgCO_2eq/m^2$)** | |
|---|---|---|---|---|---|
| | | **D1 Failure** | **D2 Failure** | **D1 Failure** | **D2 Failure** |
| **Granular Rock Fill (Control)** | Low Estimate | 120.1 | 258.0 | 50.7 | 109.0 |
| | Medium Estimate | 154.7 | 334.3 | 65.4 | 141.3 |
| | High Estimate | 189.3 | 410.7 | 80.0 | 173.6 |
| **Willow Poles** | Low Estimate | 8.8 | 19.4 | 3.7 | 8.2 |
| | Medium Estimate | 10.4 | 24.4 | 4.4 | 10.3 |
| | High Estimate | 13.1 | 29.4 | 5.5 | 12.4 |
| **Fibre Reinforced Soil (FRS)** | Low Estimate | 36.4 | 83.4 | 15.4 | 35.3 |
| | Medium Estimate | 36.5 | 83.6 | 15.4 | 35.3 |
| | High Estimate | 36.6 | 83.8 | 15.5 | 35.4 |
| **Electrokinetic Geosynthetics (EKG)** | Low Estimate | - | 32.8 | - | 13.9 |
| | Medium Estimate | - | 33.2 | - | 14.0 |
| | High Estimate | - | 33.5 | - | 14.2 |

For the deeper failure depth (2.5m, D2) scenarios the trend is much the same. The Willow Pole insertion is the least environmentally burdensome technique, having a total impact ranging between 19.4 to 29.4 $TCO_2e$, or 8.2 to 12.4 $kgCO_2e/m^2$. At this failure depth the EKG is the second most environmentally friendly technique, relative to Granular Rock Fill Replacement, with a total impact of 32.8 to 33.5 $TCO_2e$ , or 13.9 to 14.2 $kgCO_2e/m^2$. It must be noted that the impact from this method is likely to slightly higher as cathode assembly and constituent material transportation is not accounted for in this assessment due to a lack of available data. The second most impactful technique is FRS, with a total impact profile ranging from 83.4 to 83.8 5 $TCO_2e$, or 35.3 to 25.4 $kgCO_2e/m^2$. Again, the technique with the most environmentally impactful profile, in terms of global warming potential is Granular Rock Fill Replacement, with a total impact of 258 to 410.7 $TCO_2e$, or 109 to 173.6 $kgCO_2e/m^2$. Relative to the Granular Rock Fill Replacement, the impact of the Willow Pole technique is 7.2 to 7.5%, EKG is 8 to 13% and the impact from FRS ranges between 20 to 32% of the control.

The Willow Pole repair technique had the lowest impact carbon profile of those it should be remembered that this is for a cradle-to-site assessment. A small percentage of the willows planted is likely to die and thus release carbon. In addition, coppicing will create wood waste; however, this latter burden is offset by the fact that the coppicing will prompt the willows to throw out more new stems and thus capture more carbon. The carbon sequestration potential of willows is unassessed, but could act to minimise the impact of the technique if viewed over a long enough time horizon; notwithstanding that such a time horizon is unlikely to be met in the environment of road earthworks (Hill et al. 2007).

In some scenarios, depending on the quantity of materials required, the transportation steps can be responsible for generating a significant share of the total impact. For instance, in the control case of Granular Replacement, transport accounts for between 55 and 73% of the total impact, for both failure depths. The same trend is apparent for the Willow Poles technique and transport accounts for between 44 and 63% and between 26 and 51% of the impact of the shallow failure and deep failure repairs respectively.

However, In the case of FRS transport accounts for between 2.1and 2.6% of the total impact for both failure depths. This is due to two factors: relative to other techniques this method only requires a small mass of materials, and secondly large quantities of soil are moved between sites but over a relatively short distance of 0.5km. For this technique the majority of the impact originates from the production of the polypropylene strips, as these are made from oil based products. Similarly, transport in the EKG technique accounts for only 1.5 to 3.4% of the total impact. However this figure should be treated with caution as the impacts of transporting the constituent materials of the cathodes and anodes to their point of assembly has not been included in the analysis. With regard to EKG the highest impact process is the consumption of diesel to power the system during the 42 day treatment period. Second to this is the embodied impact originating from the production of the constituent materials. If the EKG design were to utilise energy generated through renewable means this could result in the system having a significantly reduced carbon footprint.

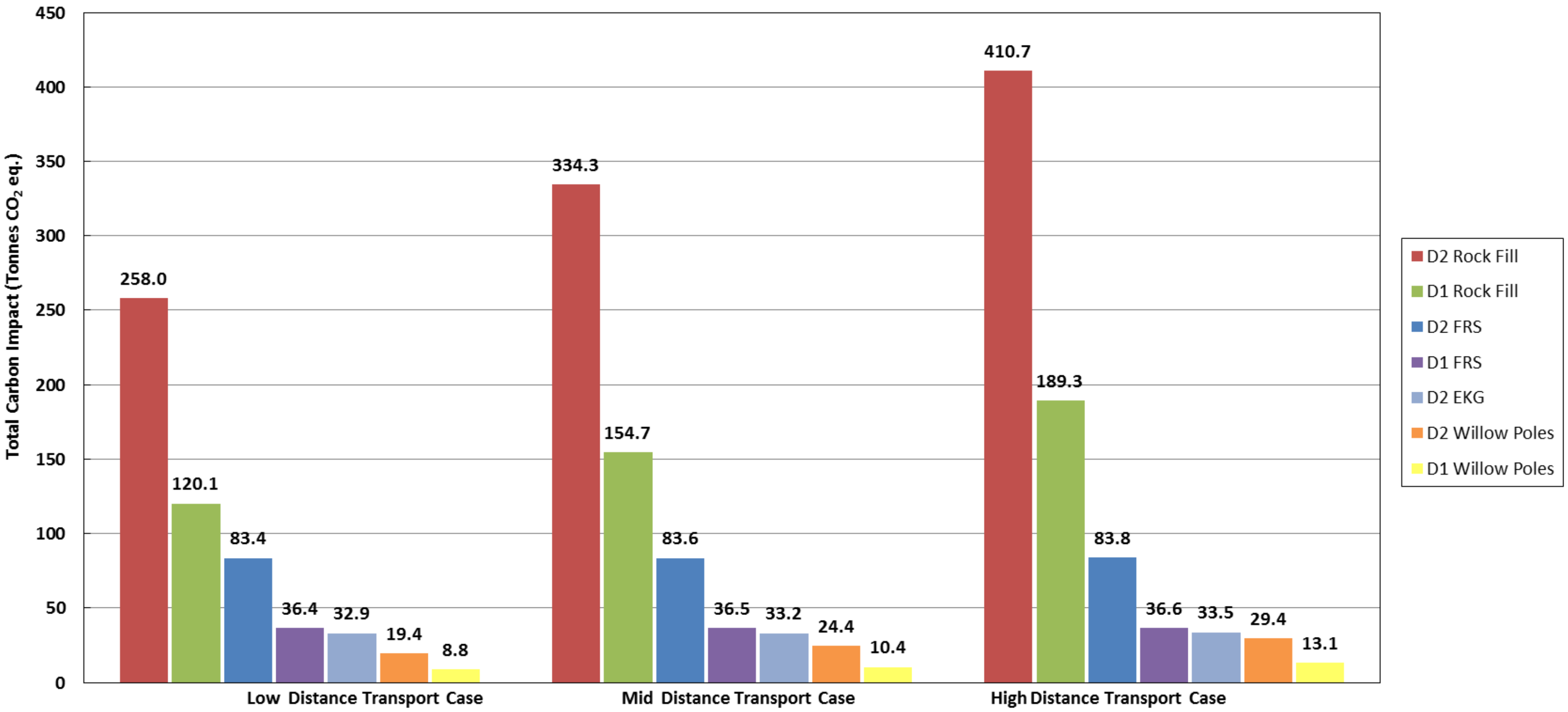


**Figure 2: Total impact comparison**

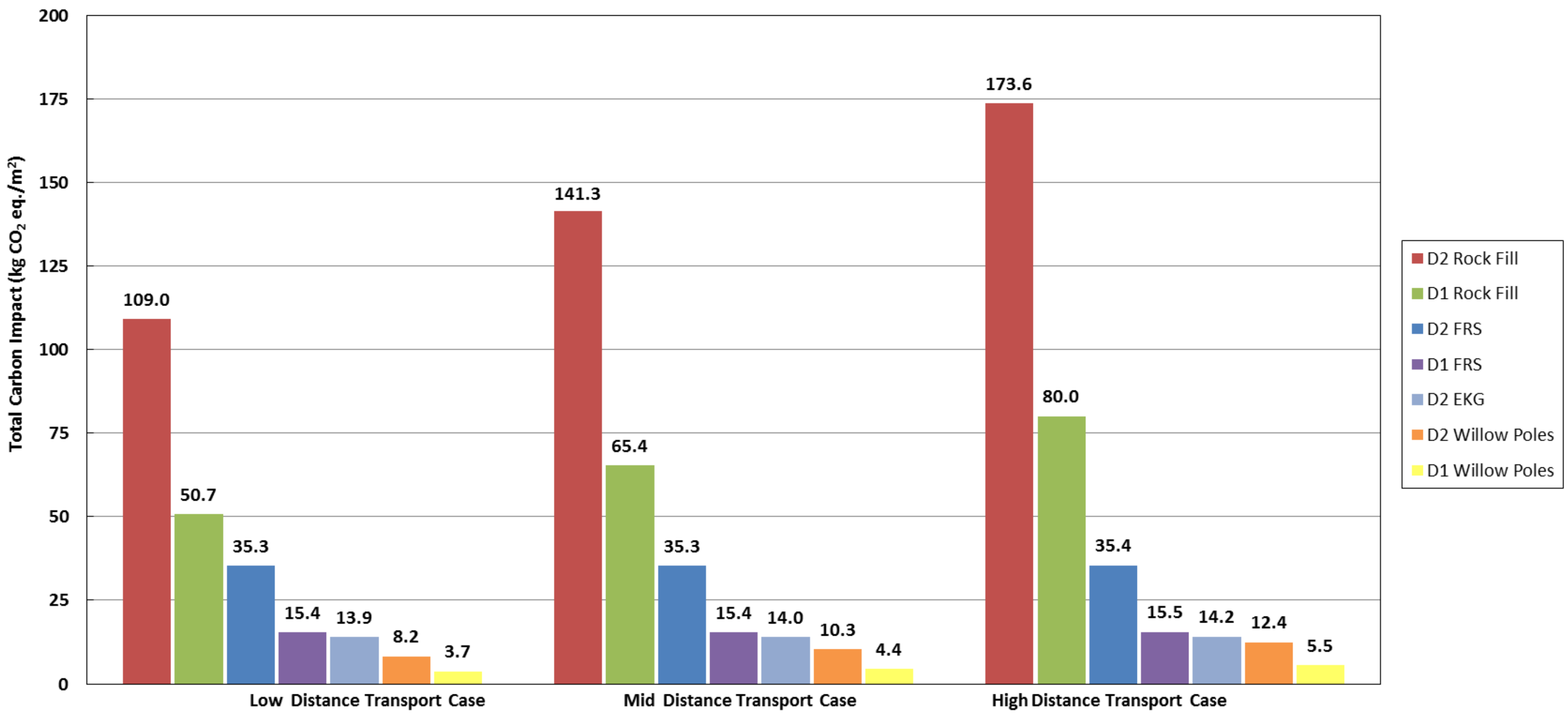


**Figure 3: Areal impact comparison**

# 5 Conclusions

This study set out to provide an estimate of the carbon impact of four slope repair techniques applied to failures on a slope 10m high, 100m wide, inclined at an angle of $25^{o}$ and with shallow and deep failure depths of 1m and 2.5m. The four techniques were Granular Replacement (control), Willow Pole planting, FRS, and EKG. All were all compared using a cradle-to-site life cycle assessment. Five life cycle steps were defined and assessed, from the acquisition and processing of the constituent materials of each installation, through to the construction of the final product – a repaired slope. A cradle-to-site LCA boundary was adopted (using the cut-off approach), as opposed to a full cradle-to-grave assessment. This approach was adopted for a number of reasons. Firstly, each of the techniques has different maintenance requirements, occurring in uneven time frames. Secondly, end-of-life scenarios for each technique vary in ways that would not allow for an equal comparison, even though the design life will be 60 years for each. Data was compiled from a number of representative sources and where possible was selected for UK specific values. Transport was calculated using tonne.km factors for a range of delivery vehicles, depending on the material and scenario. All transport was calculated for two-way (full outward-empty return) journeys.

This study provided a range of general estimates and as the slope under assessment was hypothetical, it did not have a real-world location. As a consequence it provides estimates based on assumed low-medium-high distances for transport. The functional unit of analysis was the ability of each technique to stabilise $1m^2$ of failed slope.

It was found that at both failure depths, and for all transport cases, the technique with the greatest environmental impact was the Granular Replacement, which is the conventional technique used as a control. At 1m and 2.5m failure depths this technique resulted in an impact of 51 to 174 kgCO2e/m2 of failed slope respectively, depending upon the transport distance assumed. Willow Poles had the least impact, resulting in 4 to 12 kgCO2e/m2 of failed slope respectively. For the 2.5m failure depth EKG was the second best performing technique (EKG was not assessed for the 1m failure depth scenario), with an impact of around 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 (such as the Granular Replacement and Willow Pole planting), it was found that transportation accounts for more than 50% of the total impact.

The environmental performance of the Willow Poles and EKG indicate significant environmental benefits and savings when compared to the Granular Rock Fill Replacement. FRS also shows considerable savings compared to Granular Rock Fill but the savings are much less.

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Winter, M G, R Seddon, & I M Nettleton. 2018. Innovative geotechnical repair techniques: effectiveness of willow poles. *Published Project Report PPR 874.* TRL, Wokingham.

# Innovative Geotechnical Repair Techniques

This report provides estimates of the carbon impacts of four remedial techniques used to stabilise a twenty-five degree highway slope 10m high and 100m wide for failure depths of 1m and 2.5m. The four techniques are Granular Rock Fill Replacement, which was used as a control), Willow Pole planting, Fibre Reinforced Soil (FRS), and Electrokinetic Geosynthetics (EKG). These were all compared using a cradle-to-site life cycle assessment. Five life cycle steps were defined and assessed, from the acquisition and processing of each installation's constituent materials, through to the construction of the final product – a stabilised slope.

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 per metre square and between 109 and 174 kgCO2e per metre square of failed slope respectively, depending upon the transport distance assumed. Willow Poles had the least impact, resulting in 4 to 8 kgCO2e per metre square to 8 to 12 kgCO2e per metre square of failed slope respectively. For the 2.5m failure depth EKG was the second best performing technique (EKG was not assessed for the 1m failure depth scenario), with an average impact of 14 kgCO2e per metre square. FRS had an impact ranging between 16 and 35 kgCO2e per metre square. 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.

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