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Forensic Examination of Critical Special Geotechnical Measures: Reinforced Soil Information Note

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Executive Summary

The effective design, specification and construction of Special Geotechnical Measures (SGMs) is critical to the efficient operation of the National Highways Strategic Road Network (SRN). Given the required performance of the SRN in terms of resilience, reliability, redundancy and recovery it is essential that SGMs are themselves reliable in terms of performance and life; resilient to external conditions such as earthworks deterioration and extraordinary conditions (e.g. climate change). Around 100 different types of SGMs are used on the SRN. The early installations of some SGMs are approaching the end of their design life and the design, specification and application of many of these techniques is based on limited studies.

This Information Note on reinforced soil is part of a series that reports on investigations of specific SGMs and makes recommendations on their future use. Typically, detailed accounts of issues identified on the Strategic Road Network (SRN) are given as found from inspections of the SGMs in various settings. However, for reinforced soil a lack of available sites that could be inspected during the project, primarily the deconstruction of SGMs, necessitated an approach using sources related to recent construction issues on the Strategic Road Network (SRN) and the experiences of the authors.

There is no compelling evidence that when properly designed, specified, constructed and maintained, including an appropriate inspection regime, reinforced soil SGMs cannot meet the required design life. There is, however, a clear need to reinforce the content of volume one of the Manual of Contract Documents for Highway Works (MCHW 1) to clarify what is and is not permitted for use on the SRN, especially in regard to polymeric reinforcement and to make a clear distinction between walls (structures) and strengthened earthworks (slopes).

A series of recommendations is made for all types of reinforcement, along with recommendations specific to metallic and polymeric reinforcement. It is also recommended that the MCHW 1 as it pertains to reinforced soil be subject of a full rewrite to ensure that the future use of such techniques in SGMs and structures is fully controlled. Overarching recommendations include increasing the early involvement of operational and maintenance geotechnical input and a move to cease the practice of contractor self-certification.

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1 Introduction

This Information Note on reinforced soil is part of a wider study of the performance of critical Special Geotechnical Measures (SGMs) (Duffy-Turner et al., 2022) and is one of a series that reports on investigations of specific SGMs, in this case those that include both metallic and polymeric reinforcing elements and makes recommendations on their future use.

Reinforced soil includes solutions incorporating components of Metallic Reinforcement (MTLK), defined as *metallic reinforcement such as straps or mesh, usually used in conjunction with a facing system for strengthened earthworks;* or Geogrids (GEGD), defined as *slopes of any angle reinforced using geosynthetic grids which interlock with the fill material*. Polymeric reinforcing straps used in conjunction with a facing system are also included in this work although there is not as yet a specific SGM category for such materials.

Lots of studies from around the globe have been undertaken on reinforced soil assessing the design, construction and performance of such walls and slopes. This Information Note is based on existing information from works undertaken on the Strategic Route Network (SRN), information on historic structures, and on third-party observations of contemporaneous structures. In this it differs from the other Information Notes in this series which are based on extensive inspections undertaken by the authors and supplemented by additional relevant observations by third parties where available.

2 Principles

There is a long history of the successful use of both polymeric and metallic reinforced soil, and in the UK such constructions have been used since the early-1970s.

The process was first described by Vidal (1969) and relied upon stiff, usually metallic, reinforcing elements placed in layers to reinforce the fill placed behind a wall comprised of discrete facing panels. In that respect it is different to other reinforced soil systems that rely on more flexible polymeric (geogrid or geotextile) materials to provide the reinforcing effect. This distinction between the two types of system is not made in the Manual of Contract Documents for Highway Works (MCHW). Figure 1 illustrates the first reinforced soil wall (using Vidal's 1969 process) constructed in the UK in 1972/3.

Figure 1: The first reinforced soil wall constructed in the UK at Lindsay Road, Edinburgh (from Winter et al., 2002)

In principle, metallic and polymeric reinforcement are near-identical in their application. However, there are fundamental differences in the stiffness of the elements used to achieve the reinforcement function. Metallic reinforcement is the stiffest type of reinforcing element and the potential stability, and cost, mean that typical applications include steeper walls faced with precast panels; the facing panels assist with stabilising the front face of the fill/reinforcing and crucially provide resistance to allow tension to be mobilised and interlock created between the fill and reinforcing during construction.

Geogrid is considerably less-stiff than metallic reinforcement and can be applied as a wrapped face or in conjunction with facing-panels as above; in both instances, the forces applied during the compaction of the fill layers is relied upon to mobilise tension and create interlock between the fill and the geogrid, and to thus activate the reinforcing process.

It is important to note that the design of solutions using polymeric reinforcing straps is somewhat different to the classic Vidal (1969) approach to metallic reinforcement due to the significantly lower stiffness of the polymer creating an inherently less stiff structure. In addition, such polymeric straps have been used to attach anchor blocks to the face in anchored earth walls (e.g. Brady et al., 1994a).

Reinforced soil may also be implemented using even less stiff geosynthetics including, for example, some woven and non-woven geosynthetics in a wrap-around configuration; however, these are not considered in this Information Note.

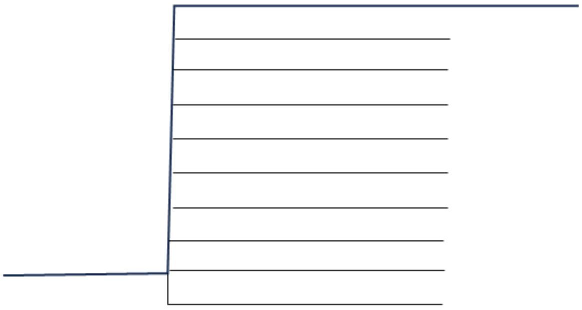
Galvanised steel elements are most commonly used in modern reinforced soil walls and care is required to avoid damage to the galvanisation during installation and compaction of the layer of fill immediately above.

One of the unknowns is how the galvanised steel reinforcing will have corroded, if at all, during the life of such structures. In this context, Blight & Dane (1989) reported on the deterioration of a metallically reinforced soil wall due to the corrosion of galvanised steel reinforcements. While such instances are seemingly rare the work of Blight & Dane (1989) was reported some 30 years ago and the potential service life of such structures is now up to around three times that which it would have been at the time; accordingly, making assumptions about the durability of such structures may well be inappropriate. A study by Beckham et al. (2005) examined galvanised steel reinforcing elements in walls approximately 40 years into their service life. While corrosion was encountered, they also found that where large sized uniformly graded fill material had been used corrosion was minimised. This is likely to be a finding that is more widely applicable to backfilled steel structures.

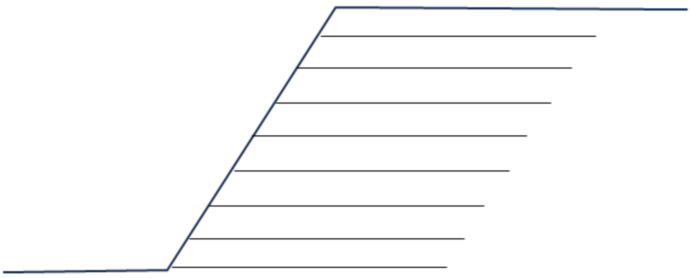
There is a clear distinction to be made between reinforced soil walls and reinforced soil slopes (Figure 2):

- Reinforced soil walls have a face inclination from the horizontal greater than 70°, are considered structures and have a 120-year design life. In the UK, reinforced soil walls are designed to Section 6 of BS 8006-1 using either the coherent gravity method or the tie back wedge method.
- Reinforced soil slopes have face inclinations up to or equal to 70°, are considered earthworks and have a design life of 60 years. Reinforced soil slopes can be subdivided into steep slopes, face inclination between 45° to 70°, and shallow slopes, up to 45°. Reinforced soil slopes are designed to Section 7 of BS 8006-1, with internal stability typically checked using circular and non-circular limit equilibrium methods. The partial factors used in the design of reinforced soil walls and abutments and reinforced soil slopes are different.

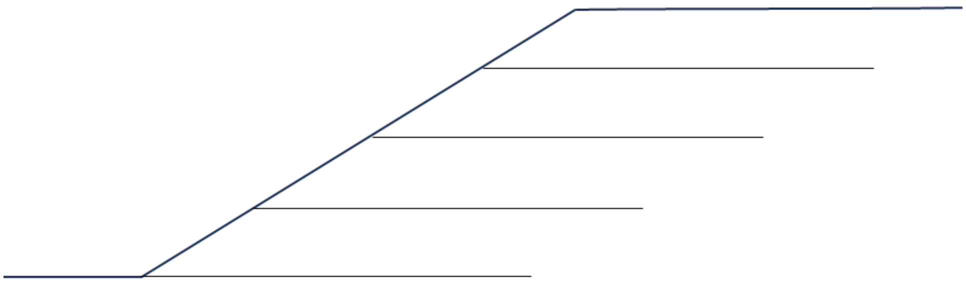
The majority of the observations in this report relate to reinforced soil walls.



a) Reinforced soil wall (>70°)



b) Reinforced soil slope (between 45° and 70°)



c) Shallow reinforced soil slope (slopes up to 45°)

Figure 2: Types of reinforced soil discussed in this report

2.1 Guidance

Table 1 summarises guidance for reinforced soil elements.

British Standard BS 8006 (2010a) provides comprehensive guidance for the design and specification of reinforced soils, as does CIRIA SP123 (Jewell, 1996). Specification and construction advice is also available in British Standard BS EN 14475 (2006), together with some considerations for design. The MCHW provides useful information on specification and construction in Series 600 and 2500, in particular for metallic reinforcement.

Table 1: Matrix of relevant documentation available for reinforced soil

Level of information provided: Background (red), Marginal (amber), Comprehensive (green)

		Relevant to:					
Publisher	**Document number and title**	GEGD Design	GEGD Specification	GEGD Construction	MTLK Design	MTLK Specification	MTLK Construction
BSI	BS 6031 (BSI, 2009) Code of practice for earthworks	Background	Background	Background	Background	Background	Background
BSI	BS 8006-1+A1:2016 (BSI, 2010a) Code of Practice for strengthened/reinforced soils and other fills	Comprehensive	Comprehensive	Marginal	Comprehensive	Comprehensive	Marginal
BSI	BS EN 14475 (BSI, 2006) Execution of special geotechnical works – Reinforced fill	Marginal	Comprehensive	Comprehensive	Marginal	Comprehensive	Comprehensive
BSI	BS EN 13251 (BSI, 2016) Geotextiles and geotextile-related products, Characteristics required for use in earthworks, foundations and retaining structures	Background	Comprehensive	Background			
NH	MCHW Vol 1 Series 600 Earthworks (622) / Series 2500 Special Structures (2502)	Background	Marginal	Marginal	Background	Comprehensive	Comprehensive
CIRIA	CIRIA (Perry et al., 2003) C592 Infrastructure embankments - condition appraisal and remedial treatment	Background	Background	Background	Background	Background	Background
CIRIA	CIRIA (Jewell, 1996) SP123 Soil reinforcement with geotextiles	Comprehensive	Comprehensive	Marginal			

3 Issues

It has not been possible to identify sites, within this project, at which the exhumation of reinforcing elements has been taking place. Therefore, the issues surrounding reinforced soil have been identified from a review of National Highways projects and the authors' experience and is not exhaustive.

Although beyond the scope of this Information Note, Anchored Earth systems are also provided for in the MCHW and the rules regarding the use of specific materials are broadly similar to those for reinforced soil. Many of the issues explored herein are also relevant to Anchored Earth.

The primary issues surrounding reinforced soil identified by Duffy-Turner et al. (2022) are as follows:

1. Potential presence of walls constructed in the 1970s using ferritic stainless steel reinforcing elements that are subject to pitting corrosion (Winter et al., 2002).
2. Installation damage of galvanised steel reinforcing elements which could potentially lead to loss of design life; notwithstanding this properly adhering hot-dip galvanisation should exhibit self-healing behaviour.
3. Poor verticality due to poor design and construction guidance and/or construction practices leaving the completed wall at too great an angle to the horizontal (Winter, 1999).
4. Excessive installation damage of geogrids (cuts, tears and abrasion) (Brady et al., 1994b).
5. Durability of geogrids, particularly where parts might be exposed to UV-light, and cuts, tears and abrasions associated with operation and maintenance activities (Brady et al., 1994c; McGown et al., 1995; Winter & Cross, 1995). Other potential related issues include the effects of fires on vegetated faces, which may become more frequent in the light of climate change.
6. Issues surrounding buildability when polymer straps are used with rigid wall facing panels particularly in achieving verticality (see also item (3) above).
7. Poorly/incorrectly specified fill materials, which is important for metallic reinforcing elements but especially so for polymeric reinforcing elements.
8. Linked to (7) above, ensuring adequate drainage both around and within the fill is essential and, as is common with drainage, often not achieved as well as might be hoped.

It is assumed that the intention of the MCHW is to allow for both metallic and polymeric reinforcing elements. However, it is worth noting that while Clause 622 specifically states that reinforcing elements shall be in compliance with that clause and Clause 2502, nowhere are polymeric elements mentioned. Indeed, as Clause 622 requires that reinforcement complies with Clause 2502, which deals only with metallic reinforcement (Clause 2502.3, 2502.4 and 2502.6), it could be argued that the MCHW effectively precludes the use of polymeric reinforcement other than through:

- the provisions of Clause 2502.5, which allows the use of proprietary reinforcing elements and systems that have a current British Board of Agrément Roads and Bridges Certificate, and
- the use of Class 7B Selected conditioned pulverised fuel ash cohesive material which may only be used with non-metallic reinforcing elements.

3.1 Issues for all Types of Reinforcement

The design and construction of reinforced soil (slopes and walls) are specialist activities. It is important that experienced and knowledgeable designers lead the process; that appropriately high levels of workmanship are applied by experienced contractors and that the construction is supervised by appropriately knowledgeable and experienced individuals.

3.1.1 Fill

The MCHW (Table 6/1) allows for a wide range of fill types for reinforced soil, as follows:

Class 6I: Selected well graded granular material (as *Fill to reinforced soil and anchored earth structures*). When the material is imported to site and is not 'as dug' it shall conform to BS EN 13242 (BSI, 2007a) (see Tables 6/1 and 6/7).

Class 6J: Selected uniformly graded granular material (as *Fill to reinforced soil and anchored earth*). When the material is imported to site and is not 'as dug' it shall conform to BS EN 13242 (BSI, 2007a) (see Tables 6/1 and 6/7).

Class 7B: Selected conditioned pulverised fuel ash cohesive material (as *Fill to structures and to reinforced soil*). Class 7B may only be used with non-metallic reinforcing elements (Clause 622.3).

Class 7C: Selected wet cohesive material (as *Fill to reinforced soil*).

Class 7D: Selected stony cohesive material (as *Fill to reinforced soil*).

Class 7B has been used successfully but its availability in large quantities tends to restrict its use. Classes 7C and 7D are less widely used for reinforced soil walls due to the higher fines content and the increased likelihood of wall movement but are more commonly used for reinforced soil slopes.

The allowable grading envelope is common for Classes 6I and 6J (Table 6/2: MCHW 1) and is wide as is clear from Figures 3 and 4. Table 6/1 (MCHW) specifies a lower limit on the uniformity coefficient of 10 for Class 6I material and lower and upper limits of five and 10, respectively, for Class 6J material. The uniformity coefficient is defined as $C_U = D_{60}/D_{10}$. The uniformity coefficient essentially prevents materials that are either too uniformly graded and too well-graded being used.

However, Figure 3 also shows the lines for $C_U \geq 10$ for values of D_{10} representing the full range of the grading envelope (i.e. $0.063 \leq D_{10} \leq 0.5$mm), with each colour representing a unique value of D_{10}. Thus, the grading must fall to the right of the appropriate coloured line to satisfy the requirements of a Class 6I material.

Figure 4 shows a similar arrangement for Class 6J materials. Here, the paired coloured lines (solid and dashed) represent the envelopes for $5 \leq C_U \leq 10$ for values of D_{10} representing the full range of the grading envelope (i.e. $0.063 \leq D_{10} \leq 0.5$mm), with each coloured pair of lines representing a unique value of D_{10}. Thus, the grading must fall between the pairs of coloured lines to satisfy the requirements of a Class 6J material.

Some recently used materials may not have fulfilled the requirements for coefficient of uniformity and it is suggested that this feature of the specification for fills should form the focus of additional quality checks in the future. This may be an issue that needs to be addressed more widely than simply in respect of reinforced soil walls. It is noted that the use of fill with appropriate properties is critical to the successful construction of reinforced soil walls (and slopes).

The angularity of individual fill particles may be an issue for polymeric straps (see Section 3.3.2) and should be addressed in any modifications to the MCHW if the use of such systems is to be retained.

3.1.2 Drainage layers

Clause 622.5 refers to horizontal drainage layers and vertical drainage accommodation behind the wall facing. In general, such drainage layers should not normally be needed if the fill used conforms to the requirements of either Class 6I or 6J. However, where such drainage accommodation is needed, it should conform to the requirements of Class 6H.

Drainage of the walls and supporting cuttings around reinforced soil structures is covered in detail in Section 6.10.5 of BS 8006-1, BS EN 14475:2006, ISO TR 18228-4:2022 and Rimoldi (2016). Most drainage issues arise due to poor detailing of the drainage system during design and/or poor workmanship during construction. Type B filter material conforming with the requirements of Clause 505 may be used only in horizontal drains.

Notwithstanding this, where Class 7B fill is used, Clause 622.5 requires the use of a drainage material based on BS EN 12620 (BSI, 2015).

Vertical drainage layers are required to be brought up at the same rate as the adjoining fill to minimise instability of fill faces and to minimise the contamination of the drainage media by the fill, the latter is especially important where a geosynthetic separator is not used.

3.1.3 Facings

Clause 2502.12 to 2502.15 allows for metallic, concrete and proprietary facings.

No provision appears to be made for the use of reinforced soil without the use of rigid facing panels, which is particularly important for polymeric materials that can deteriorate through the action of ultraviolet light (see Section 3.3.1). This is, however, somewhat obscured by the presence of Class 7B material, which is only for use with non-metallic reinforcement and the provision for the use of proprietary systems in Clause 2502. Typical rigid facing panels are shown in Figures 5 and 6.

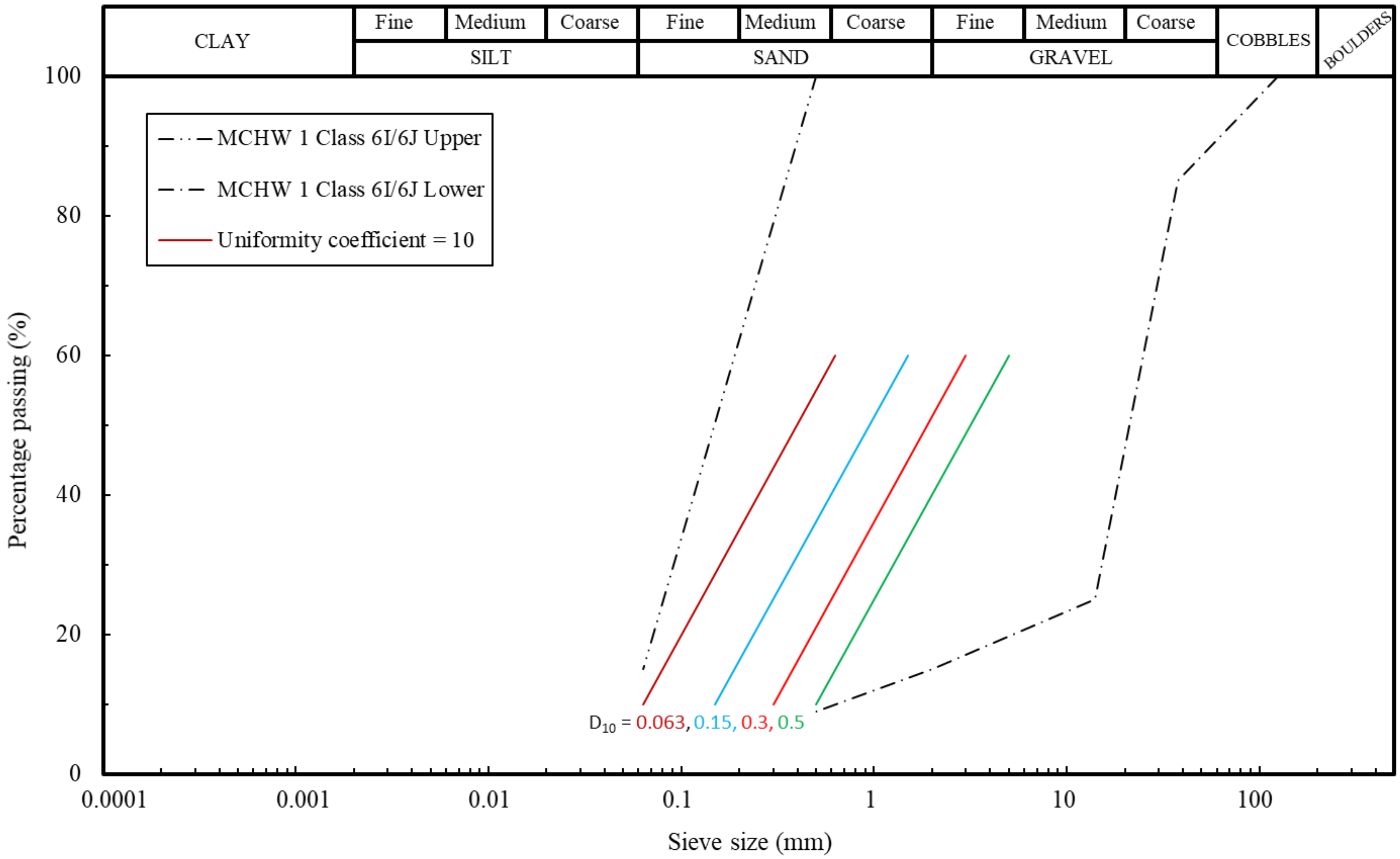


Figure 3: Grading envelopes and coefficient of uniformity requirements for Class 6I and 6J materials. The limits for coefficient of uniformity are based on a range, 0.063 ≤ D_{10} ≤ 0.5mm with each colour representing a value of D_{10} within that range. The area to the right of each coloured line and the MCHW 1 Class 6I/6J Lower Limit define the zone into which the particle size distribution must fall for the corresponding D_{10} value to satisfy the requirements for Class 6I.

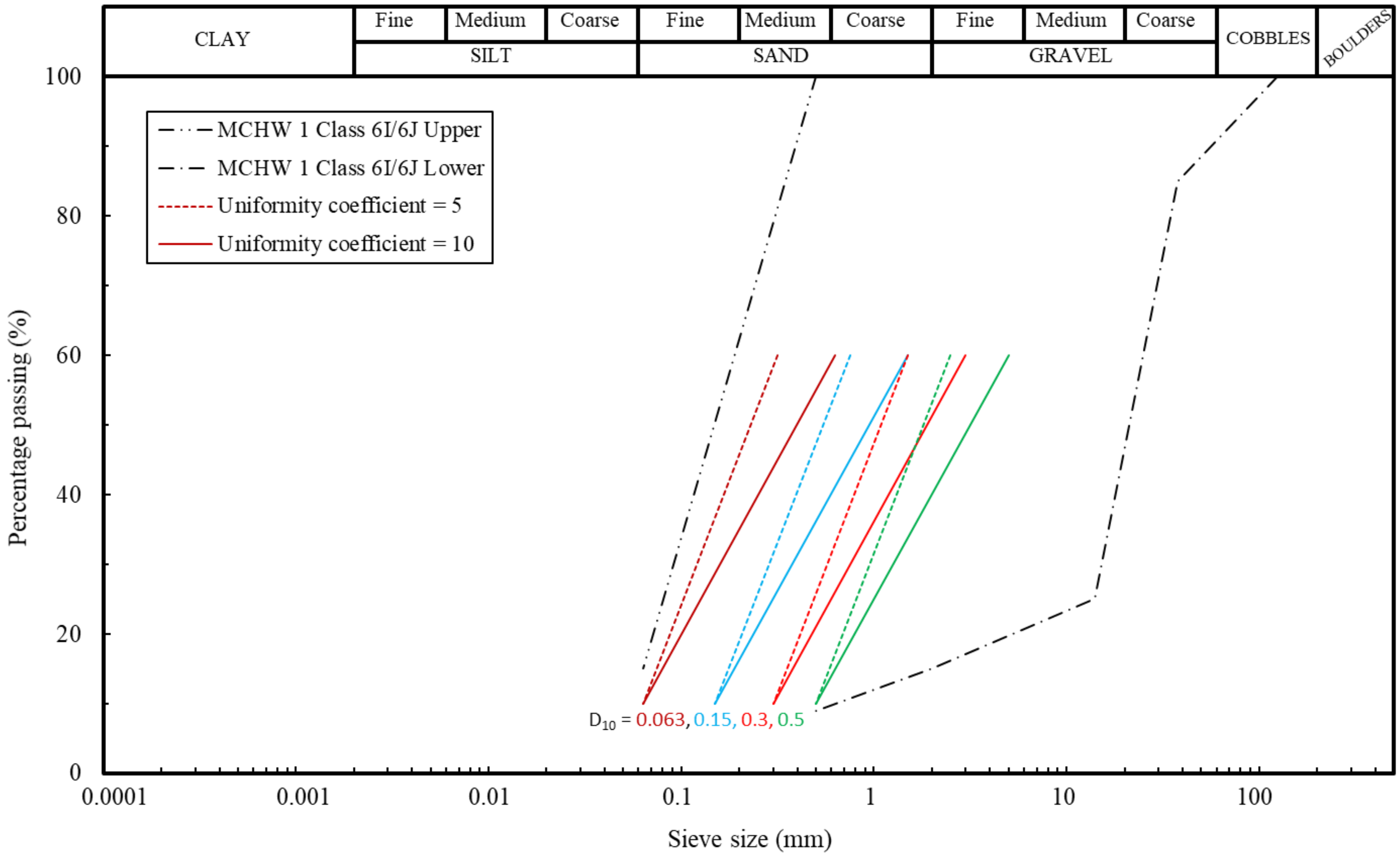


Figure 4: Grading envelopes and coefficient of uniformity requirements for Class 6I and 6J materials. The limits for coefficient of uniformity are based on a range, 0.063 ≤ D_{10} ≤ 0.5mm with each colour representing a value of D_{10} within that range. Each coloured pair of coloured solid and dashed lines defines the zone into which the particle size distribution must fall for the corresponding D_{10} value to satisfy the requirements for Class 6J.

Figure 5: Reinforced soil wall under construction at A96 Brechin Bypass (image the authors)

BS8006-1 Table 18 (BSI, 2010a) and BS EN 14475 (BSI, 2006) place clear requirements on the location of the plane of the structure, overall verticality, and bulging and bowing in a 4.0m linear template. What it does not do is to place limits on steps between facing panels or the vertical and horizontal alignment of individual panels. Significant issues with such alignments have been experienced on the SRN; these have been related to reinforced soil walls constructed with rectangular facing panels with polymer reinforcing straps (as opposed to a polymer grid) and a typical example is illustrated in Figure 7.

Figure 6: Reinforced soil wall under construction at M8 Junction 2 (Claylands) (from Winter, 1999)

While this is initially an aesthetic issue, it is also likely to be an ongoing issue for inspection and maintenance. The misalignment of the panels seemingly results from issues surrounding the buildability and the application of poor standards of workmanship during the construction of such walls (see also Section 3.3.2). It is further recognised that cruciform-shaped panels do not manifest this issue.

Figure 7: Misalignment of individual facing panels to a polymeric reinforcing; sections of these walls project have been built/rebuilt at least three times (Image National Highways)

3.1.4 Verticality

The construction guidance relies heavily on the constructor's assessment of how much panels will move during construction (Figure 8). Such movements are influenced by the fill, which can be very sensitive to moisture changes and the fines content, the stiffness of the reinforcement, the friction at the interface between the reinforcement and fill, and the mass of compaction plant used close to the panels, for example, and control of these factors is critical in order to obtain the desired verticality. BS EN 14475 (BSI, 2006) Clause C.1.2, notes that reinforced fill earth retaining structures may have a vertical, battered or inclined face. Notwithstanding this, there appears to be little or no information on the final angle of the constructed wall relative to the vertical (face batter) in design guidance or specifications; such requirements seem to be largely left to Works-specific documents such as the MCHW Volume 1 Appendix 1/10 and/or the construction drawings. BS 8006-1 (BSI, 2010a) Table 18 does, however, give commonly achieved construction verticality tolerances, that are meant to be read as the tolerance from the designed face batter and it is clear that these are intended only to be indicative values.

The mass of vehicles and plant, including compaction plant, that may be operated within 2m of the rear of the facing panels is limited to a maximum of 1,000kg (MCHW 1 Clause 622.7(iv) to 9(v)) in order to limit the stress placed on the material placed immediately behind the panels and the potential for outwards movement during construction.

Figure 8: Reinforced soil wall under construction at M8 Junction 2 (Claylands) (from Winter, 1999)

3.1.5 Installation damage

One of the primary considerations with reinforced soil relates to the durability of the reinforcing material during both construction and in-service. Brady et al. (1994b) reported that geogrids were potentially prone to splitting damage during installation (construction), particularly when installed in coarse-grained soils.. Although this seems to correspond well with the data retrieved from the National Highways Geotechnical and Drainage Management System (GDMS), in which the most common form of damage to geogrids is 'tears', this is not necessarily attributed to installation damage (Duffy-Turner et al., 2022). Where installation damage is considered likely it should be accounted for by the use of reduction factors as typically contained in the British Board of Agrément (BBA) certificate, or equivalent, for the system.

Note that there are standard tests available to assess construction damage BS EN 10722 (BSI, 2007b) and BS EN 17738 (BSI, 2023).

The MCHW 1 (Clause 622 (7) (iii) requires that both metallic and polymeric reinforcement elements shall be *"… kept as free of damage as possible during deposition, spreading, levelling and compaction … (… no machines or vehicles run on the reinforcing or anchor elements).*" The mass of vehicles and plant, including compaction plant, that may be operated within 2m of the rear of the facing panels is also limited to a maximum of 1000kg in order to limit damage to the reinforcing elements as well as prevent outward movements as discussed in Section 3.1.4.

Clause 2502.7, which deals only with metallic reinforcement, further requires that the elements shall be "… *prefabricated and delivered to Site ready for installation into the Works*", while this may seem to indicate that reinforcing elements may not be cut to size after manufacture; more typically materials are cut, but in mitigation, further protective measures are added such as using galvanised paint on the exposed ends and allowance made for corrosion (e.g. cut 100mm longer than the design requires). The Clause goes on to state that

"The elements shall be:

"(i) Loaded, unloaded and handled in such a manner that:

"(a) no permanent set or other structural damage is caused;

"(b) the protective coating is not damaged.

"(ii) Stored flat …"

The form of typical metallic (galvanised steel) reinforcing elements can be seen in Figure 6.

3.2 Issues for Metallic Reinforcement

3.2.1 Permitted Materials

The MCHW deals with the use of steel for multiple applications, including for reinforced soil. This leads to a rather wide range of permitted materials. The use of some of these materials in reinforced soil, such as stainless steel, is not in line with practice or experience in the UK or elsewhere. The following paragraphs summarise some of the more relevant parts of the MCHW. This highlights the need for a more focussed, or reinforced soil-specific, approach to future editions of the MCHW.

Clause 2502 of MCHW 1 permits the use of various grades of carbon steel strip as defined in BS EN 10025-1 (BSI, 2004) and BS EN 10025-2 (BSI, 2019). A silicon content of between 0.25% and 0.40% is specified to increase deoxidation, strength and hardness. Post-fabrication hot dip galvanization is also required in accordance with MCHW Clause 1909.

Stainless steel BS EN 10029 (BSI, 2010b), BS EN 10048 (BSI, 1997a), BS EN 10051 (BSI, 2010c), BS EN 10258 (BSI, 1997b) and BS EN 10259 (BSI, 1997c) designation 1.4401 or 1.4436 are also permitted. Both designations are for austenitic stainless steel with both seemingly being equivalents of ASTM AISA Type (or Grade) 316, which would not normally be considered suitable for use in reinforced soil.

Proprietary reinforcing elements and systems that have a British Board of Agrément Roads and Bridges Certificate are also permitted.

Clause 2502.16 requires that all buried metallic components (i.e. reinforcing elements, connections, facing lugs and facing units) shall be of electrolytically compatible material. Where this is not possible, effective insulation is required to be provided between different materials.

3.2.2 Corrosion

Limiting the corrosion of metallic reinforcing elements is critical to the successful application of reinforced soil systems.

A study by Beckham et al. (2005) examined galvanised steel reinforcing elements in walls approximately 40 years into their service life. While corrosion was encountered, they also found that where large sized uniformly graded fill material had been used corrosion was minimised. Similarly, Greene & Brady (1999) noted that while, over a 20-year in-service life, corrosion was evident in galvanised mild steel reinforcing elements intensive pitting corrosion was not evident. With a design life of 120 years it is considered that some effort toward establishing longer term behaviour might be worthwhile (see Section 3.4).

Many of the requirements of the MCHW are focussed on limiting corrosion of metallic components generally and the requirements range from the specified material; through minimising damage during prefabrication, handling, transport, installation and compaction; to ensuring electrolytic compatibility of all buried metallic components.

Notwithstanding these measures, there is a requirement on the designer to undertake an assessment of the corrosion potential of the proposed reinforcing in the context of the fill used and the wider environment. Early work on this subject was reported by Eyre & Lewis (1987) and specific tests are incorporated into the BS1377 series (BSI, 1990, 2021) while Entwisle et al. (2015) give guidance on the spatial distribution of relevant properties. The perils of a mismatch between reinforcing and fill (Winter, 1998) were amply illustrated by the deterioration of the reinforcing elements used in the UK's first reinforced soil wall at Lindsay Road in Edinburgh (Winter et al., 2002; Figure 9).

Figure 9: Lindsay Road reinforced soil wall – excavation of ferritic stainless steel reinforcing elements (from Winter et al., 2002)

De-icing agents used to limit ice on the SRN have the potential to accelerate the corrosion of metallic reinforcing elements. The infiltration of such agents from the verge of a road above a reinforced soil wall seems to be more likely than their entry from facing panels adjacent to a road. However, this seems to be an area which has not been researched extensively with only experimental studies known to date (e.g. Kolay et al. 2017). Whether de-icers enter from the facing panels or from the verge above, their effects are, in most instances, likely to be at or close to the front face of the wall and partial or complete facing panel detachment seems to be the most likely outcome. Techniques for facing panel replacement are described by Anon. (2010a, 2010b).

If the entry of de-icers is from the verge of a road above the wall, then such detachment is likely to have a limited, immediate effect on the overall stability of the wall although the consequences of the detachment on any elements below is greater due to the potential height from which the panel may fall. Similarly, entry of de-icers via the facing panels, as a result of spray from a road in front of the wall, is likely to affect the lower facing panels having a greater effect on overall stability but less potential damage from the complete detachment, and fall under the action of gravity, of facing panels. This seems to be an issue that has been less than fully investigated and further work may be needed.

3.2.3 Legacy Materials

It is clear that the MCHW does not allow the use of ferritic stainless steel, which used to be known as Type (or Grade) 430. Indeed, BSI (2006, Clause 6.3.2.4) clearly states that “Stainless steel or aluminium alloys should not be used for soil reinforcement in permanent structures unless for particular cases and based on specific studies”. Ferritic stainless steel is highly susceptible to pitting corrosion (Murray, 1992), however it was used for the first three reinforced soil walls constructed in the UK. The first such wall was built in 1972/3 and extensively investigated by Winter et al. (2002) after significant corrosion was encountered (Figure 9) and was subsequently decommissioned. The other two walls are believed to have been constructed on the SRN, but their exact locations and current status, whether extant or decommissioned, are unknown.

The fill used for the first wall was Spent Oil Shale which can have high sulfate contents (Winter, 1998; Winter et al., 2002). This combination was found to be the cause of the severe corrosion observed in the reinforcement that led to the wall being condemned. This combination of reinforcing and fill materials was particularly problematic, but ferritic stainless steel in isolation, with a more appropriate fill material, was also considered to be highly problematic and is not allowed in the MCHW (the construction of the Lindsay Road wall and other such walls pre-dates such coverage in the UK Specification for Highway Works). Consultations at the time of the work on the Lyndsay Road investigations (*circa* 1999) with those active in reinforced soil in the 1970s suggested that at least two other walls were believed to have been constructed using ferritic stainless steel, with unknown fill types, on the National Highways SRN and none were known to have been deconstructed in the interim. One was believed to be in the Wigan/Warrington area, but the exact location was unknown and could not be readily determined, while the location of the other was not known. The location and continued existence of these walls is unknown at the present time. These walls were identified from the knowledge and recollections of senior professionals at the time of the Lyndsay Road investigation; despite extensive enquiries within the National Highways geotechnical community, particularly in the north-west, both around 1999 and during the currency of this project neither the existence nor the location of these walls has been confirmed.

It is recommended that the potential presence of these walls be highlighted in some manner, to the wider geotechnical supply chain in order that when and if they are encountered appropriate action can be taken in a timely fashion.

3.3 Issues for Polymeric Reinforcement

3.3.1 Ultraviolet

Historically a great deal of work has been undertaken to understand the effects of UV on the properties of geosynthetics. This has led to changes in the manufacture of materials such that UV deterioration is less likely within the design life of modern geosynthetics when used as intended. It may be encountered in legacy products installed on the SRN.

In the UK it is not appropriate to build walls and abutments without facing panels so UV exposure will not be an issue for reinforced soil walls. In addition, slopes up to 45° are unlikely to require a wraparound, or wrap back, detail at the face so there will be no exposure of the geogrids. Slopes between 45° and 70° may require a facing panel or wrap around detail and some form of protection may be necessary. This may be in the form of vegetation, but the establishment thereof can be problematic on slopes in the steeper end of the range and some other form of sacrificial covering may be needed. In such instances reduction factors may be used as typically contained in the British Board of Agrément (BBA) certificate, or equivalent.

3.3.2 Use of Polymeric Straps

The use of polymeric straps with rigid facings has a long history of successful use in the UK, including on the SRN. This dates back to the 1970s as for other forms of reinforced soil.

Strap systems were first used with metallic reinforcing straps that are high stiffness (inextensible). Notwithstanding that, there tends to be some compaction-induced movement/rotation of the individual facing panels during construction and initial facing alignment tends to be at a slightly raked back angle to allow for such movements.

The use of polymeric straps in combination with rigid facing panels introduces a flexibility into the reinforced soil wall system. To achieve the strains required to mobilise the design tensile strength of the straps, complex and, for the inexperienced constructor, difficult-to-execute construction systems have been used on some recent projects.

These have included arrangements involving the use of open trenches, parallel to the wall, part way along the reinforcing straps and the anchoring of reinforcing straps with pins to keep the straps in place and under light tension (Figure 10), albeit that the requirements of BS EN 14475 Clause 8.5.3.2 (BSI, 2006) should be observed. The trenches are then filled as part of the placement and compaction of the subsequent fill layer so pre-stressing the straps to minimise movement as the wall height is increased. Walls constructed in this manner have had significant misalignment of the panels (Figure 7) and the buildability issues led to cycles of construction, deconstruction, and reconstruction. While it is not entirely clear that this is caused by the trench system, it may be a function of the fill used and/or poor workmanship and/or supervision. Jones & Hughes (2024) speculate that this could be the source of damage to the reinforcing, but significant further work is required to verify this. The techniques involving initial inclination of panels, trenches and anchoring of straps are subjective and place the responsibility on the installer to produce a finished product that meets aesthetic requirements without dislocated and/or misaligned panels. Buildability is also understood to be particularly problematic with this type of trenching system at corners where there is significant interference between straps.

Such a system seems unnecessary as both locating pins and tensioning bars have been used successfully in the past without the potential negative effects described above. It is worth noting that the tension needed in the straps should be sufficient to ensure that the reinforcement is tight and that any slack has been removed, to minimise any deformation during the mobilisation of tensile forces (BS EN 14475, Clause 8.5.3.2). Although not always practical, provided that the fill is placed initially immediately behind the wall and worked towards the distal ends of the straps the removal of any slack by hand and the application of a small amount of tension applied in this manner is usually sufficient (Damians et al., 2015; Brouthen et al., 2022).

Figure 10: Polymeric reinforcing straps with rigid concrete facing panels showing the trench used to tension the straps along with anchoring of the straps (Image National Highways)

Clearly, reinforced soil is a specialist activity and requires specialised and experienced installers. While the technology and concept are well understood, experience is still required to construct these walls. Careful supervision by experienced engineers is required during construction of reinforced soil walls. This along with the use of fill with appropriate properties, restricting plant movement within two metres of the internal wall face, as required by the MCHW, is critical to successful construction of reinforced soil walls.

3.4 Future Investigative Opportunities

Over a three-year period encapsulating one of the most intense periods of road infrastructure renewal in England, it proved impossible to identify and visit sites containing reinforced soil

SGMs at a time that they were being excavated. This simply illustrates the difficulty of taking an ex-post approach to achieving a greater understanding of the performance of such SGMs.

It is recommended that the potential presence of walls constructed using ferritic stainless steel be highlighted in some manner, to the wider geotechnical supply chain in order that when and if they are encountered appropriate action can be taken in a timely fashion.

3.5 Overarching Issues

Throughout this project, contractor self-certification has been raised and evidenced as one of the most significant issues that leads to poor construction. The issues may not be apparent at the time of construction and therefore may not be addressed by the designer or client, leading to subsequent poor performance and early-life failure of not only SGMs but other forms of construction. Indeed, this issue has been highlighted on other National Highways projects on which the authors have worked and in work for other infrastructure owners and operators both in the UK and overseas.

A high-profile example of this is found in the Earthworks Task Force Report (Mair, 2021) on the Carmont Rail Disaster, which notes in the context of water management, drainage assets and the associated risks that "*There is very limited supervision of drainage work by [Network Rail], with a reliance on contractor self-certification*".

It is considered that a move to cease Contractor self-certification and revert to a more conventional client-led Construction Quality Assurance scheme in order to ensure quality of execution of Works is strongly indicated. The use of contractor self-certification is not considered to be in the best interests of any party including the client, designer and, indeed the contractor.

Also strongly indicated is, earlier and more extensive operational and maintenance geotechnical input to Major Works in order to ensure specification compliance, acceptability for use and handover to the operator.

4 Recommendations

There is no compelling evidence that when properly designed, specified, constructed and maintained, including an appropriate inspection regime, reinforced soil SGMs cannot meet the required design life for either slopes (60 years) or for structures (120 years) of such SGMs.

Notwithstanding this it is considered that some adjustments to the current MCHW requirements are indicated, and these are set-out below as a series of recommendations that apply either to all types of reinforcement or to either metallic or polymeric reinforcement. It is also considered that a significant refresh of the current MCHW as it pertains to reinforced soil would reap benefits and this along with some wider recommendations are also set out below.

4.1 All Types of Reinforcement

Recommendation 1: Some recently used fill materials may not have met the requirements for coefficient of uniformity and it is suggested that this feature of the specification for fills should form the focus of additional quality checks in the future. This may be an issue that needs to be addressed more widely than simply in respect of reinforced soil walls.

Recommendation 2: Careful supervision by experienced engineers is required during the construction of reinforced soil walls. It is recommended that National Highways consider the most appropriate means of achieving that end in order to improve the outcomes from reinforced soil construction.

4.2 Metallic Reinforcement

Recommendation 3: The effect of de-icers on metallic reinforced walls and slopes is an issue that has been less than fully investigated and further work may be needed. In the first instance this might take the form of estimates or modelling of the quantity of de-icers entering SGMs both above and below road level, the associated acceleration of the corrosion rate and the consequential loss of stability. The results from such work could then inform the basis of decisions on whether more detailed and complex physical investigations and tests would be required to refine the understanding of such effects.

Recommendation 4: While the MCHW permits the use of certain stainless steels BSI (2006) effectively excludes their use; it is not recommended to use these materials in practice in the construction of reinforced soil walls. This highlights the need for a detailed rewrite of the MCHW with regards to permitted materials for reinforced soil walls.

Recommendation 5: Notwithstanding **Recommendation 4** above, three walls constructed in the UK in the 1970s used ferritic stainless steel and two of those may remain on the network. It is recommended that the potential presence of these walls be highlighted in some manner, to the wider geotechnical supply chain in order that when and if they are encountered appropriate action can be taken in a timely fashion.

Recommendation 6: Information on the in-service deterioration of galvanised reinforcing elements is limited. It is recommended that a planned approach to gathering such information is implemented. This would involve the placement of sacrificial reinforcing 'coupons' that can be recovered without deconstruction of the wall at pre-defined time intervals after construction.

4.3 Polymeric Reinforcement

Recommendation 7: In the UK only reinforced slopes between 45° and <70° will not require a facing panel but will require a wraparound, or wrap back, detail and some form of protection may be necessary. This may be in the form of vegetation, but the establishment thereof can be problematic on slopes in the steeper end of the range and some other form of sacrificial covering may be needed. In such instances reduction factors should be used as typically contained in the British Board of Agrément (BBA) certificate, or equivalent, for such systems.

Recommendation 8**:** Further to ***Recommendation 7***, it is recommended that the MCHW 1 should include a requirement that all reinforcing geosynthetic materials exposed at the surface of slopes (between 45° and 70°) be fully covered whether by soil or vegetation in order to limit the risk of adverse impact on such materials due to fire, caused by arson, and other forms of vandalism such as the cutting of the geosynthetic materials. The hazards of vehicle fires or wildfire, especially in the context of climate change, remains.

4.4 Reinforced Soil and the MCHW

Recommendation 9: It seems clear that some realignment of the existing MCHW 1 will be required in order to implement the recommendations given above. In addition, the current MCHW 1 has evolved over a number of decades in respect of reinforced soil. There currently is a lack of clarity with respect to where and how polymeric reinforcement is allowed to be used and under what circumstances and at what angles to the horizontal slopes and/or walls may be formed. The specification focusses largely upon walls at angles of 70° and above to the horizontal. It is considered that a rewrite of this part of the MCHW 1 (principally Clauses 622 and 2502) to encompass specific requirements on the use of both metallic and non-metallic reinforcements is indicated and would provide significant benefits by helping to ensure that reinforced soil is used appropriately and constructively. The following observations are made for such a rewrite:

- The current specification for metallic reinforcement is generally reasonably comprehensive but could be usefully simplified and clarified.
- A similar approach is needed for polymeric reinforcement, and this should clearly distinguish between strengthened earthworks (slopes of <70°) and walls (structures ≥70°).
- Be clear on what systems and reinforcement types are permitted for strengthened earthworks and structures.
- It is also suggested that, where appropriate, the specification should clearly indicate systems and reinforcement types; these might include, for example, ferritic stainless steel and the use of polymeric straps for walls/structures or otherwise in combination with rigid facing panels.

- Updates should recognise developments in reinforcing technologies and afford the relevant professional bodies an opportunity to make an independent contribution to the update process.

It is recognised that the timescale and nature of the current MCHW update will not accommodate such changes, which will require careful deliberation and consultation, and it is recommended that this be considered for the following MCHW update cycle.

4.5 Overarching Issues for all SGMs

It is considered that a move to cease Contractor self-certification and revert to a more conventional client-led Construction Quality Assurance scheme in order to ensure quality of execution of Works is strongly indicated.

Also strongly indicated is, earlier and more extensive operational and maintenance geotechnical input to Major Works in order to ensure specification compliance, acceptability for use and handover to the operator.

The effective implementation of these two recommendations increases the likelihood that Works are built correctly first time and greatly reduces the risks associated with future defects and deterioration. This becomes even more critical in the light of predicted climate change which is expected to exacerbate geotechnical asset deterioration.

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Forensic Examination of Critical Special Geotechnical Measures: Reinforced Soil Information Note

The effective design, specification and construction of Special Geotechnical Measures (SGMs) is critical to the efficient operation of the National Highways Strategic Road Network (SRN). Given the required performance of the SRN in terms of resilience, reliability, redundancy and recovery it is essential that SGMs are themselves reliable in terms of performance and life; resilient to external conditions such as earthworks deterioration and extraordinary conditions (e.g. climate change). Around 100 different types of SGMs are used on the SRN and the early installations of some SGMs are approaching the end of their design life and the design, specification and application of many of these techniques is based on limited studies. This Information Note on Reinforced Soil is part of a series that reports on investigations of specific SGMs and makes recommendations on its future use.

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