

# INNOVATIVE DESIGN OF REINFORCED SOIL WALL ON A STEEP SLOPE SUBJECT TO LAND SLIP RISKS

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## ABSTRACT

This paper presents a case study of an innovative reinforced soil wall (RSW) design on steep slope using site-won material that is not in full compliance with Roads and Maritime Services (RSM) QA specification R57. The steep slope was impacted by a landslide occurred in February 2010. Firstly the local geology and the landslips occurred along the project corridor are briefly described. The key design and material requirements for RSW have been reviewed with respect to the use of site-won material. A detailed strategy is presented on how to deal with the potential risks of using the non-compliance site-won fill material to the specification R57. A comprehensive laboratory testing regime of the site-won material and large-scaled pullout tests of RSW reinforcement were undertaken. With the test results and engineering judgement, the design was proceeded with the following key assumptions/factors: 1) the allowable fines (<75 microns) content of up to 25%, clay (<2.4 microns) content of up to 7%; 2) the use of reduced friction angle of 30 degrees; 3) a 10% reduction in the calculated pullout capacity of reinforcement; and 4) 1.5 times sacrificial allowance as per R57. These were to cater for long term corrosion on steel reinforcement and to ensure longevity and integrity of the RSW. A heavy rainfall in February 2010 resulted in two significant landslips within the project corridor, with the larger one being immediate at the down slope of the reinforced soil wall (RW01). This event required us to carry out an additional geotechnical investigation and landslide remedial works to ensure the long term global stability of RW01. Three dimensional effects were considered in the assessment of the slope instability in the construction stage review.

## 1 INTRODUCTION

The design of the reinforced soil walls (RSW) for RMS projects and some other building development projects is often based on RMS specification R57 within the New South Wales and sometimes across Australia. One of the key design requirements on the RSW fill is the fines (<75 microns) content limit of not greater than 15%. A Design Alliance, comprising Roads and Maritime Services (formerly Roads and Traffic Authority) and Hyder Consulting was formed to undertake the detail design for the Great Western Highway Upgrade at Bullaburra West. The Design Alliance team investigated the feasibility of the use of site-won material from the proposed rock cuttings with higher fines content for construction of the reinforced soil walls within the project corridor. At the start of the project the Design Alliance team held a workshop and planned a series of sampling and testing programs in order to gain the confidence in preparing a comprehensive documentation for design and construct of the proposed RSWs using site-won material.

This paper describes how a rigorous planning and implementation process was carried out together with specialist testing so as to determine the design parameters appropriate for this project. In addition this paper discusses the impacts of landslips occurred in February 2010 during the detail design phase of the RSWs, in particular a large landslide at the Brown property access road. The remedial design of the Brown property access landslide to achieve a minimum factor of safety against the global instability of RSW RW01 is also presented in this paper.

## 2 PROJECT DESCRIPTION

This project consists of a 2 km highway upgrade to a separated dual carriageway of the Great Western Highway from 400 m west of Genevieve Road, Bullaburra, to Tableland Road, Wentworth Falls. The existing section of highway is one lane in each direction with overtaking lanes, and generally runs uphill from east to west, with a significant 8.5% grade up Bodington Hill. The project main elements of works, as shown in Figure 1, comprise eleven retaining walls including three RSWs (RW01, RW02 and RW04), three cuts, four property accesses including Brown Property Access and four Basins (only the permanent basin was shown and the other three temporary ones were not shown), one fauna underpass and three underbores underneath the Main Western Railway for drainage works (not shown). Cut03 is approximately 370 m long cut into the Bodington Hill on the southern side of existing Highway. Cut02 is approximately 150 m long into the Mohawk between the existing highway and the main western railway. Reinforced soil wall RW01 is about 150 m long with a maximum height of 14m, RW02 is 80 m long with a height of 10 m and RW04 is 50 m long with a maximum height of 6 m. One of the project challenges was to use the site-won material from Cut03 and Cut02 for RW01, RW02 and RW04 as shown on Figure 1. The other challenge was the remedial design of landslips induced by February 2010 storm event, in particular the landslide at Brown property access road, which would have an impact on the global stability of RW01.

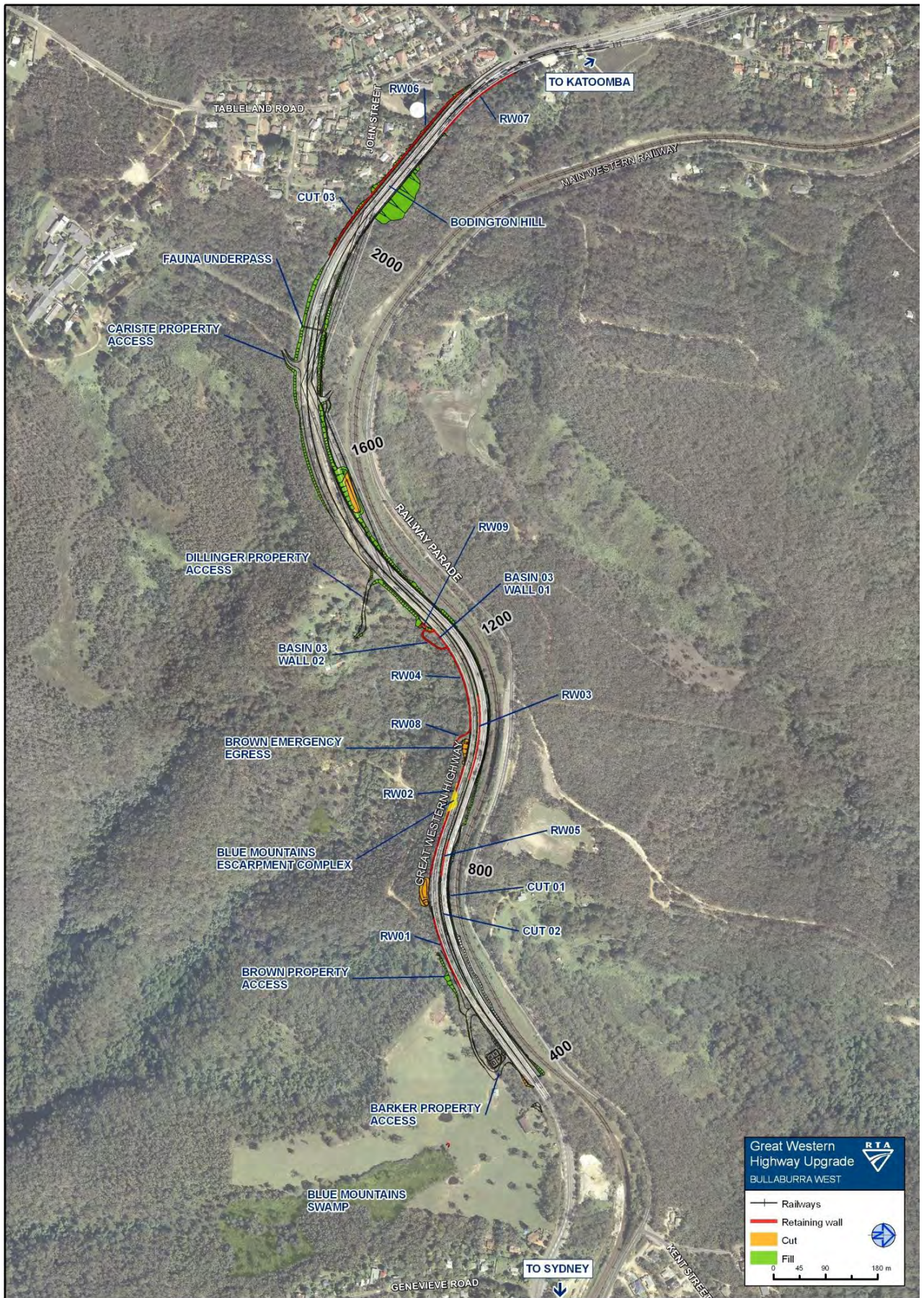


Figure 1: Locality map showing key elements of proposed works.

### 3 LOCAL GEOLOGY AND SITE CONDITIONS

#### 3.1 GEOLOGICAL SETTINGS

Reference to the Katoomba 1:50,000 geological map (Sheet 8930-1) indicates that the Bullaburra West upgrade project sites are underlain by the Banks Wall Sandstone (BWS) of the Triassic period. The BWS is generally described as quartz sandstone slightly lithic, with minor interbedded claystone. Subsurface conditions within the site generally comprise varying thicknesses of sandy soils overlying sandstone bedrock and there are numerous rock outcrops and cuttings along the highway corridor.

BWS across the project site is generally red to orange brown, typically extremely to highly weathered, extremely low to very low strength, highly friable, medium to fine grained and has closely spaced joints/fractures. Ironstone veins are frequently encountered within the sandstone matrix at varying depths.

#### 3.2 LANDSLIPS

During a storm event in February 2010 three landslips occurred over the project corridor. These are at:

- Station 635 – This was a relatively small slip with a width of about 10m around the toe of the embankment of the access road to the Brown’s property.
- Station 660 – This was a large-scale landslip that occurred at the edge of the access road to Mr Brown’s property.
- Station 1150 – This was a major landslide that occurred at the identified uncontrolled fill area. It was found from the historic data that a similar scale of landslide occurred around 1960.

The primary cause of the landslip was the erosion/washout induced by either surface water or seepage through the embankment or at the interface between embankment and bedrock.

The landslips that occurred across the project corridor complicated the detailed design process and documentation. The remedial design strategy for the landslips that occurred at Station 660, which would have an impact on the RSW RW01 global stability, is briefly described in this paper.

## 4 GEOTECHNICAL UNITS AND DESIGN PARAMETERS

#### 4.1 GEOTECHNICAL UNITS

A concept site investigation was undertaken by RMS prior to tendering. An additional site investigation was carried out jointly by Hyder and RMS between 2009 and 2010. A geotechnical factual report was prepared by RMS in March 2010. Hyder subsequently prepared an interpretation report in April 2010. An addendum to the geotechnical factual report was prepared for the Brown property access investigation in May 2011 by RMS, and the results were interpreted by Hyder in June 2010. A summary of the geological units, depth range and characteristics for the project based on the geotechnical interpretative report is presented in Table 1.

Table 1: Geotechnical profile of project site

Geological Unit	Depth Range (m)	Description	Comments
Unit 1A	0-2	Fill: Sand and or Sandy soil of residual origin, medium dense to dense.	Generally encountered at most of the drilled boreholes and the thickness of the layer various along the project corridor
Unit 1B	0-9.9	Fill and Colluvium: Sand and Gravelly Sand, dense to very dense.	Maximum depth of 9.9m encountered at down slope of the Bodington Hill cut and approximate 6-8m fill was encountered at Brown access road.
Unit 2A	>20	Banks Wall Sandstone: Highly to moderately weathered, low to medium strength sandstone bedrock.	Generally greater than 20m with no indication of strength increase with depth observed from all boreholes drilled across the project site.
Unit 2B	0-3	Banks Wall Sandstone: Extremely to highly weathered, extremely low to very low sandstone bedrock.	Occasionally present within Bodington Hill cut as identified from mapping and borehole drilling.

## 4.2 GEOETCHNICAL DESIGN PARAMETERS

As part of the geotechnical investigation targeted soil sampling and testing was carried out during the detail design stage. Some samples were collected from the borehole auger drilling, cores and some from the bulk excavation trenches done at the existing Bodington Hill cut. The test results indicated that most of the indices as per R57 were satisfied except for the fines content (passing 0.075mm) being higher than 15%. A series of shear box testing was also carried out to assess the shear strength of the remoulded Banks Wall Sandstone. The shear strength test results yielded the friction angle ranging from 28 degrees to 40.5 degrees (Yang *et al* 2012). A summary of the geotechnical parameters adopted for use in the project is presented in Table 2.

Table 2: Adopted geotechnical design parameters for each unit

Geological Unit/Description	Unit Thickness (m)	Unit Weight (kN/m <sup>3</sup> )	Effective Cohesion (kPa)	Effective Friction Angle (Deg)	Young's Modulus (MPa)	Permeability (m/s)
Unit 1A – Loose to very dense sand	11.4	17-19		30-38	10-80	-
Unit 1B – Uncontrolled fill	4.6	16		30	5	-
Unit 2A(1)- Extremely low to very low strength sandstone	12.6	22	23	37	100-300	1.0e-7
Unit 2A(2)- Extremely low to very low strength sandstone	12.6	22	30	44	100-300	1.0e-7
Unit 2A(3)- Extremely low to very low strength sandstone	12.6	22	15	37	100-300	1.0e-7
RSW Fill		20	0	30	60	1.0e-7

Note: a) Unit 2A(1) - Applicable to the design of soil nail wall, piled and other retaining walls; b) Unit 2A (2) - Only applicable to slope stability of the reinforced soil wall design; and c) Unit 2A (3) - Parameters used for underbore modelling to predict the settlement.

## 5 DESIGN CONCEPT DEVELOPMENT

At the concept design development stage a number of retaining wall options were considered. These includes a) piled wall with ground anchors; b) counterfort retaining wall; c) gravity retaining wall; and d) reinforced soil wall. The reinforced soil wall option was preferred for its low cost advantage. However the cut and fill material balance was an issue in that large quantities of material surplus from Cut01, Cut02 and Cut03 would have to be disposed due to presence of high fines contents, should imported fill be required for the RSW construction. As such further sampling and testing works were undertaken to assess how much fines were in the material won from these cuts.

## 6 REINFORCED SOIL WALL DESIGN CONSIDERATONS

The design of reinforced soil wall for this project required careful consideration of the following key issues: a) use of site-won material and material characterisation; b) consideration of durability aspects of the RSW system; c) constructability of the RSW on steep hillside; d) the landslide impact on RSW stability; and e) achieving R57 global stability requirements.

### 6.1 REVIEW OF RSW DESIGN CRITERIA

The specific requirements for RSW design that are either subject to further consideration or interpretation are summarised in the Table 3. R57 only allows the use of one type of RSW fill material that is defined as inert, durable material with fines less than 15% passing of 75 microns. AASHTO (2010) has similar design requirements for the RSW to those of R57. It is, however, noted that BS8006 (1995, 2010), Hong Kong Geospec 2 (1989) and subsequent Geoguide 6 (2002) allows the use of two types of fill, i.e. Type I - granular fill with fines less than 10% passing of 63 microns; and Type II - cohesive fill with fines between 10 to 45% passing of 63 microns. It can be seen that requirements of Type I material is virtually the same among R57, BS8006, AASHTO and Hong Kong Geospec 2 or Geoguide 6 except for different sieve diameter for the fines.

A summary of the key RSW material requirements and stability analysis acceptable factors of safety (FoS) and factors is presented in Table 3.

Table 3: RSW fill requirements and key design criteria

Reference	Design Method	Key RSW Fill Requirements and Design Criteria
Table R57.10 / BS8006	Property Index of RSW Fill	R57: Fines<0-15%, LL<30% and PI<12% for Fines. BS8006: LL≤ 45% and PI≤ 20% for Type II, less than 2 microns 0-10%.
Generally Acceptable Industrial Practice	Conventional global stability analysis	<ul style="list-style-type: none"> <li>A minimum global factor of safety shall be 1.5.</li> <li>All load factors are set to be 1.0. Earthquake load is not considered.</li> <li>Groundwater level is set to be at the actual groundwater level.</li> </ul>
R57 Clause 4.7.3	Global stability analysis under earthquake	<ul style="list-style-type: none"> <li>A minimum global factor of safety shall be 1.35. Load factor for static loads is set to be 1.0.</li> <li>Load factor for traffic (live) load and earthquake load is set to be 0.5 and 0.75 respectively.</li> <li>Ground water is set to be at ground surface level.</li> </ul>
Generally Acceptable Industrial Practice	Global stability analysis under extreme conditions – flooding	<ul style="list-style-type: none"> <li>A minimum global factor of safety shall be 1.2.</li> <li>All load factors are set to be 1.0. Earthquake load is not considered.</li> <li>Water level is set to be at the ground surface in front of RSW.</li> </ul>
R57	External Design (Sliding, bearing and overturning)	<ul style="list-style-type: none"> <li>The interaction factors for sliding, bearing and overturning are to be greater than 1.05</li> <li>Load Factors for Load Cases A), B), C), D), E and F are the same as per Standard RMS R57.</li> </ul>

A comparison between R57 and BS8006 regarding the allowable electrical and chemical limits of RSW fill is shown in Table 4. It can be seen that the key parameters are virtually the same between these two design guidelines. With reference to AASHTO 2010, it is noted that similar testing requirements are set for granular RSW fill. The fundamental difference is that only BS8006 and Geoguide 6 permit the use of cohesive soil for the RSW.

Table 4: Comparison of allowable electrical and chemical limits of RSW fill

Code Reference	Allowable Limits		Allowable Limits		
	R57	R57	BS8006 (1995)	BS8006 (1995)	AASHTO (2010)
	Submerged <sup>1</sup>	Non-Submerged	Submerged	Non-Submerged	
pH	5-10	5-10	5-10	5-10	5-10
Resistivity (ohm m)	≥ 30	≥ 10	≥ 30	≥ 10	≥ 30
Organic Content (%) <sup>2</sup>	N/A	N/A	≤ 0.2	≤ 0.2	≤ 1.0
Redox Potential (volts) <sup>3</sup>	N/A	N/A	≥ 0.4 (Type I) ≥ 0.43 (Type II)	≥ 0.4 (Type I) ≥ 0.43 (Type II)	N/A
Microbial Activity Index <sup>3</sup>	N/A	N/A	≤ 5	≤ 5	
Chloride Ion Content (% by weight)	≤ 0.01	≤ 0.02	≤ 0.01	≤ 0.02	≤ 0.01
Sulphate Ion Content (% by weight)	≤ 0.05	≤ 0.10	≤ 0.05	≤ 0.10	≤ 0.20
Total Sulphate Content (% by weight)	N/A	N/A	≤ 0.10	≤ 0.20	

Notes: (1) Submerged structure means a structure that is periodically submerged in water but excluding marine condition and contaminated or saline water. (2) The measurement of organic content shall be carried out for clayey soils where more than 15% passes a 63 microns BS Sieve Size. (3) The measurement of either redox potential or microbial activity index shall be carried out for clayey soils with an organic content in excess of the specified.

**6.2 RSW FILL CHARACTERISATION**

In order to better characterise the fines content from Cut02 and Cut03 the Design Alliance team undertook additional borehole drilling and coring as well as in-situ trench sampling from the existing Bodington Hill cut. Sampling and the testing procedures were kept as close as possible to normal field excavation and compaction for the reinforced soil wall. It was acknowledged that the samples obtained from auger drilling appeared to have much higher fines contents than those crushed bulk samples from the Bodington Hill cut as shown in Figure 2.

It has been noted from Figure 2 that, except for those samples taken by auger drilling, the fines content for the rock samples from Bodington Hill range from 15% to 25%. The fines content of the rock samples from the eastern cutting (in the vicinity of Cut 02) is more variable, ranging between 7% and 24%. The hydrometer testing results indicates that the clay content (less than 2.4 microns) is typically ranging from 3% to 10% based on samples from test pits where fines of less than 75 micron is less than 25%. It has been concluded that the testing results of the cored samples and trench excavation samples are more realistic, noting the treatment of sample would result in an increase in fines by 2% to 4%.

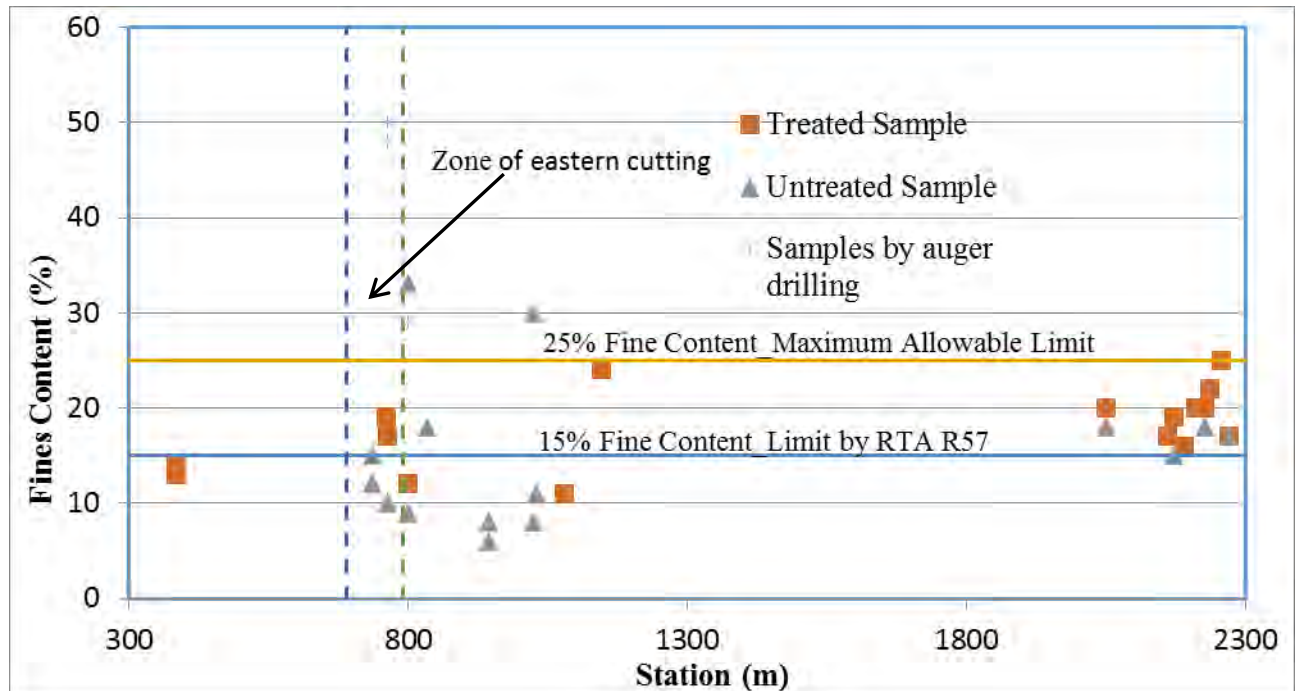


Figure 2: Fines contents of recovered samples from borehole and trenches along project alignment.

**6.3 DURABILITY CONSIDERATION**

Due to the higher fines content within the RSW fill a research of the corrosion allowance was undertaken to determine how much sacrificial allowance should be adequate at various stage of the design life. It is noted that the requirements for the electrical and chemical limits with respect to the pH value, resistivity and Chloride ion content are identical for R57, BS8006 and AASHTO. The Sulphate ion content and the organic content in AASHOT 2015 are relatively higher than those in R57 and BS8006. This was based on the findings that most constructed RSWs experienced a slower corrosion rate on the reinforcements than allowed in the design, which has a typical factor of 2 as reported by Elias (1990, 2009). However BS8006 requires additional testing for redox potential and microbial activity index for cohesive fill as shown in Table 4. The authors believe that this is due to the fact that R57 only allows the use of inert, durable material with fines not more than 15% passing 75 microns. After review of these published codes or specifications the Design Alliance team decided to refer to Hong Kong Geospec 2 (1989) which specified the use of Type II fill with fines up to 45% and clay up to 15% and an additional 50% sacrificial thickness to the metallic reinforcement.

Hong Kong Geoguide 6 (2002) indicates that the effects of loading and construction damage to metallic reinforcement may not be time dependent. Corrosion, which is related to the electrochemical nature of the soil and the air/water requirement, is time dependent and is considered as a reduction in net reinforcement cross-sectional area with time. For the conditions pertaining to reinforced soil, the effects of individual factors are additive and not interdependent. Thus rates of corrosion, for example, do not vary with load intensity.

Based on the above assessment Tables 57.9 and 57.13 in R57 were revised to include an increase in the steel corrosion allowances to cater for the potential higher level of corrosion due to presence of high fines content. The revised specific details for minimum sacrificial steel thickness on each hot-dip galvanized steel surface exposed to corrosion within reinforced the fill material are shown in Table 5 and Table 6:

Table 5: Minimum sacrificial steel thickness for hot-dip galvanized steel soil reinforcement (mm)

Design Life (Years)		5	10	20	30	50	100
Structural Location	Land Based i.e. out of water	0	0.1	0.3	0.5	0.9	1.35
Structural Location	Fresh Water Based	0	0.15	0.5	0.65	1.05	1.5

Note: (1) Linear interpolation may be used for intermediate values; (2) These values may not be applicable in the presence of stray electrical currents from adjacent power sources. In such cases values must be assessed by specific study.

Table 6: Sacrificial steel thickness for steel facing connections/facing elements and other steel components (mm)

Design Life (Years)		5	10	20	30	50	100
Structural Location	Land Based i.e. out of water (1)	0	0.15	0.5	0.65	1.05	1.5
Structural Location	Fresh Water Based (2)						

Note: (1) Linear interpolation may be used for intermediate values; (2) These values may not be applicable in the presence of stray electrical currents from adjacent power sources. In such cases values must be assessed by specific study.

#### 6.4 PULLOUT CAPACITY

The research work by Bobet (2002) has found that RSW fill with high fines content is likely to lower the pullout capacity of reinforcement under saturated condition. In addition the degree of saturation and transportation of moisture is important to the shear strength at the interface of the reinforcement against the RSW fill. Bobet (2002) also noted that when the permeability of the RSW fill is lower than  $10e-5$  m/s the dissipation of the pore water pressure is very slow, and that the pullout capacity of reinforcement may be reduced by up to 50% when a small percentage of fines is present within the RSW fill. As such the Design Alliance team proposed a pro-typo laboratory test to determine the pullout capacity of two reinforcement systems. These specialist pullout tests using the materials collected from the excavated trenches in Bodington Hill cut were undertaken on two RSW systems by the Australian Defence Force Academy (ADFA) of the University of NSW in Canberra, i.e. Reinforced Earth System and VSL Retained Earth System.

#### 6.5 SUMMARY OF KEY FACTORS CONSIDERED FOR THE NON-COMPLIANCE MATERIAL

Based on assessment and discussion with the RMS, the following measures were undertaken to mitigate the adverse effects resulting from use of site-won crushed sandstone with a fines content of up to 25%:

- Based on the grading results discussed above, increased the upper limits for particles smaller than 75 micron and 2.4 micron in reinforced fill material to 25% and 7% respectively in revised R57 for this project.
- Adoption of a slightly conservative design value of constant volume frictional angle of 30 degrees for reinforced soil fill.
- Reduction of the design values of the coefficient of interaction by 10% for pullout capacity as stipulated in the Specification R57 based on ADFA testing results.
- Provision of a dedicated drainage system using gravel wrapped in geotextile behind to minimise groundwater pressure built-up behind the RSW
- Provision of a clay liner on top of the RSW block to minimise infiltration into the RSW.
- Placement of a geotextile behind the facing panels to prevent the escape of fines from the RSW block.

## 7 RSW WALL CONSTRUCTABILITY AND DETAILS

### 7.1 RSW CONSTRUCTION STRATEGY

The Design Alliance commissioned a specialist contractor to undertake a concept design of the proposed reinforced soil walls (RW01, RW03 and RW04) along the westbound carriageway where the retained height was greater than 6 m. This particular proprietary wall type was selected for several reasons, including cost efficiency, construction method and sequencing, materials management, spatial constraints and safety.

To balance the earthworks throughout the project, it was intended to re-use the crushed sandstone as the reinforced fill material where possible on the RSWs. The site-won sandstone from Cut03 was proposed for use in RW02 and RW03.

Material from the eastern cutting (Cut02, Station 705 to 800) was proposed for use in RW01. Sandstone from temporary excavations needed for RW01 and RW02 was proposed for use in RW04. Significant temporary work was expected for the construction for these RSWs due to steep hillside.

A typical cross-section of the proposed reinforced soil wall is shown in Figure 3. A dedicated drain was applied to control the potential seepage from the uphill side and divert the seepage to the subsoil drain to a dedicated outlet points. A geosynthetic clay liner was provided at the top surface of the reinforced fill material at 2% grade to prevent subsurface water flows/infiltration into RSW fill. The water collected from the clay liner would then be drained away through a vertical drainage blanket at the rear of the RSW. To this end it is unlikely that there will be significantly free water entering the RSW block.

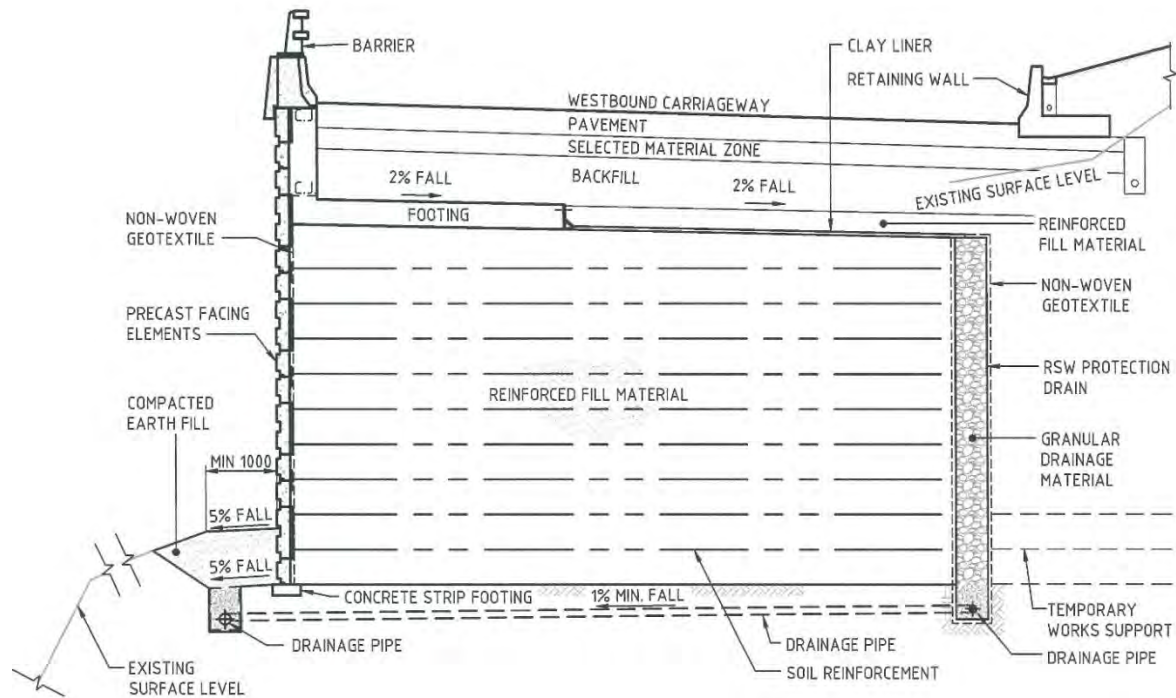


Figure 3: Typical cross-section of RSW wall.

The internal stability check was carried out by the specialist contractor, while the external stability was carried out by Hyder. It was found that the length of the RSW block was governed by the global stability rather than internal stability.

## 7.2 INTERNAL STABILITY CHECK

The internal stability check was carried out for all the load cases as per R57 with due consideration of the factors summarised in Section 6.5. An interaction factor of 1.05 rather than 1.0 was adopted to facilitate a slightly higher safety margin due to some uncertainties in soil electrical and chemical properties. The RSW internal stability checks against rupture, pullout, connection strength at the face panel and wedge failure were undertaken with due consideration of the following:

- Steel reinforcement with appropriate corrosion allowance made as per revised R57;
- 10% reduction in pullout capacity of reinforcement at the interface between steel and soil; and
- Use of a friction angle of 30 degrees for the RSW block.

## 7.3 EXTERNAL STABILITY CHECK

The external stability checks of the RSW were carried out for load cases A to F as stipulated in R57 in order to satisfy the following failure mechanisms: Ultimate Limit States: a1) Bearing failure; a2) Sliding; a3) Slip failures and b) Serviceability Limit State: Settlement, b1) tilting, eccentricity, rotational and lateral movement; and b2) Slip failures. These were carried out by the specialist contractor and Hyder.

It was found that the width of the RSW block was governed by the global stability of the potential slip plane either beyond or just passing the bottom corner of the RSW. This suggested that global stability is critical in determining the size of the RSW block width and the constructability of the RSW, in particular RW01 which is very close to the existing highway that has to remain open at all time.

The global stability of the existing embankment was analysed based on the rock and soil parameters discussed in the previous sections. This analysis indicated that the existing slopes were close to the minimum required factors of safety

of 1.35, prior to the additional loads from the retaining wall. Note that the global stability analysis assumed the design water table on the downslope side of the retaining wall to be at the proposed surface level as per R57.

A lower factor of safety than 1.35 was calculated for the sections that were impacted by landslip occurred at Brown’s property access road. As such landslip remediation was carried out prior to completion of detail design.

### 8 LANDSLIP REMEDIATION

In order to maintain the access road to Brown’s property and enhance the factor of safety against slope instability after construction of the RSW RW01, remedial works were required for the landslip approximately between Station 660 and Station 700.

A workshop was held by the Design Alliance to discuss the strategy of the Brown’s landslip remedial works. It was agreed that two cases were to be investigated:

- Case 1: The minimum factor of safety against global failure of retaining wall RW01 without repair works to the existing Brown slip;
- Case 2: The minimum factor of safety of RW01 following repair works.

Three remedial options were considered: a) Rockfill re-profiling – use rock fill deposited on the slope face to stabilise the slope to achieve the required factor of safety; b) Gabion wall - construction of a gabion wall along the shoulder of the existing access road to Brown’s property; and c) Piled wall – construction of a contiguous piled wall along the edge of existing access road.

The option of rockfill re-profiling was preferred for ease of construction, low cost and project program advantage. A maximum slope angle of 29 degrees should be maintained to achieve a minimum factor of safety of 1.35 for the RW01. In addition a rockfill containment bund was required at the toe of the slope prior to the placement of the rockfill for ease of construction. To avoid saturation of soil at the upper part of slope and subsequently instability of the slope, a drainage pipe was designed to discharge stormwater from uphill catchment beyond the point at least 16 m away from the slope crest.

It was found that the calculated factor of safety of RW01 at about Station 660 without any remedial works was approximately 1.27 as shown in Figure 4, which did not satisfy R57 requirement of 1.35. With the consideration of the remedial works the calculated FOS was enhanced to 1.40 as shown in Figure 5.

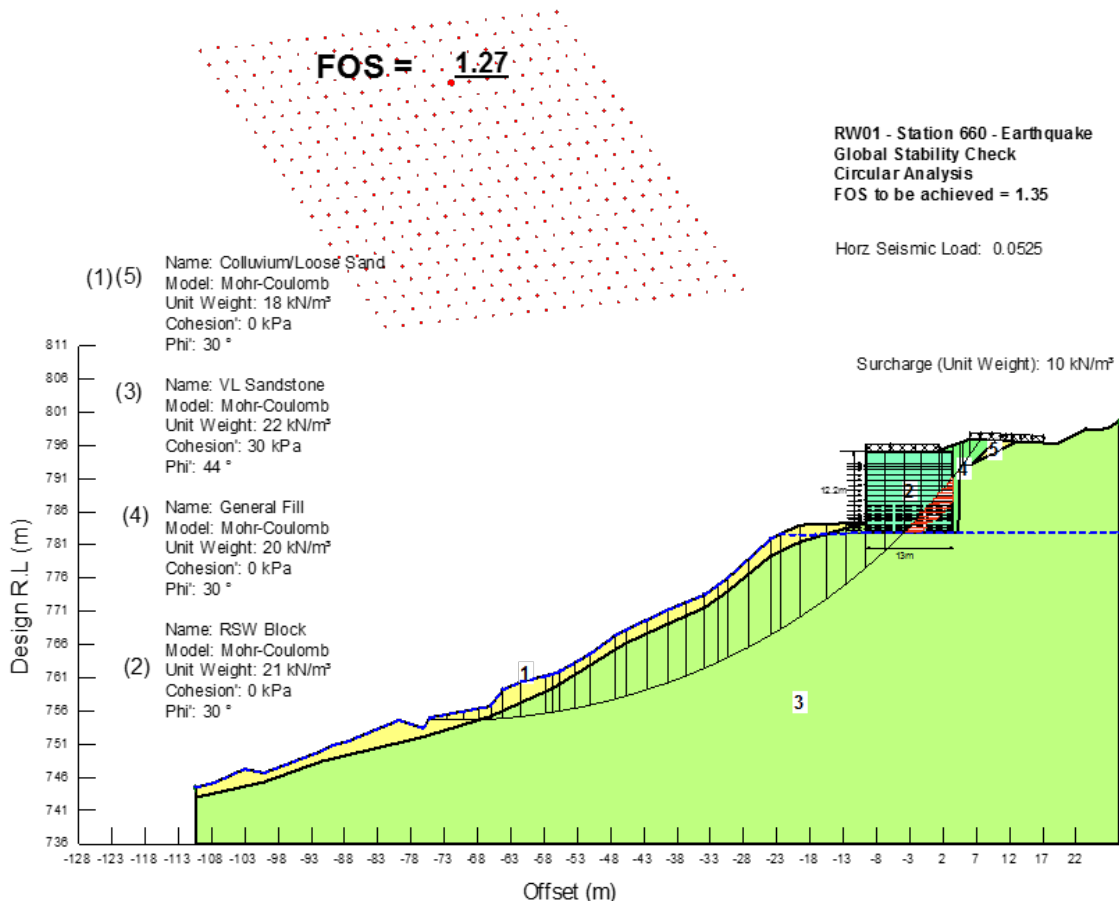


Figure 4: Calculated FoS of Slope without remedial works.

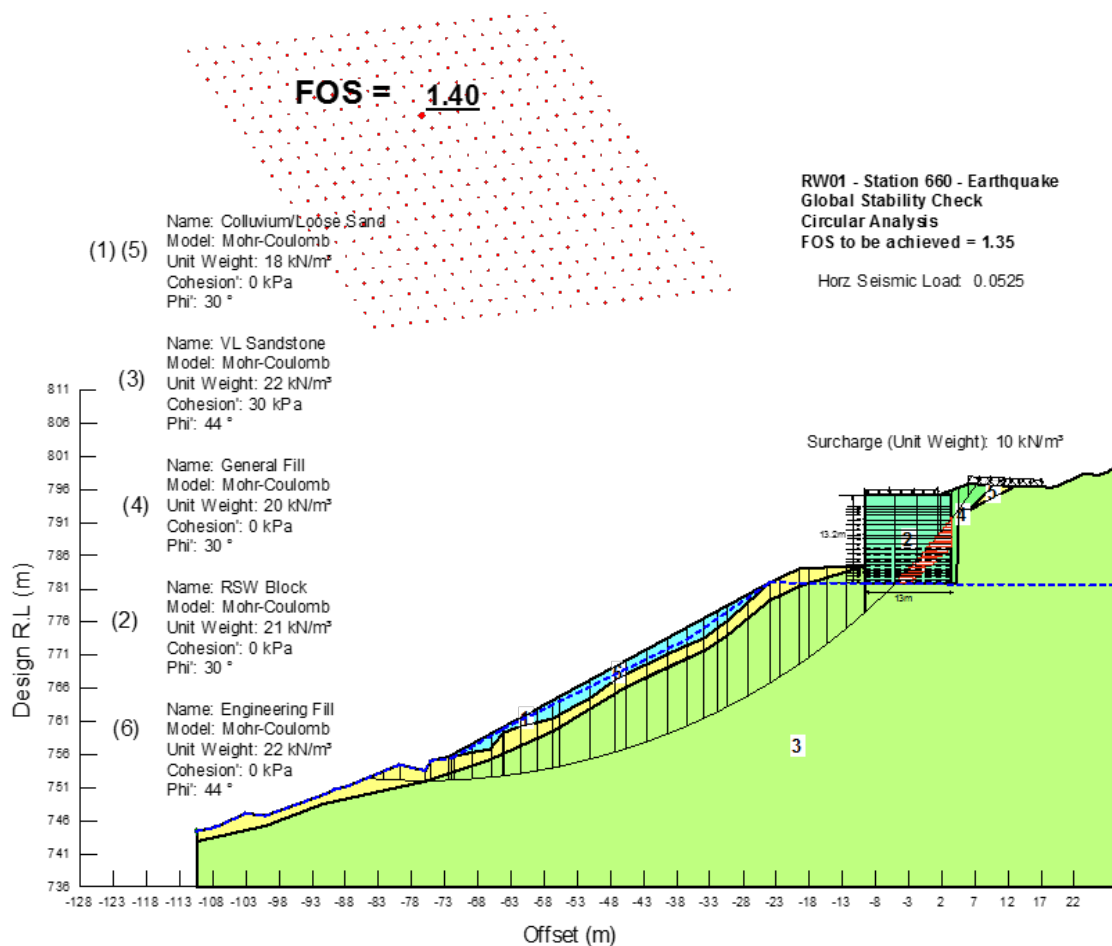


Figure 5: Calculated FoS of Slope after remedial works.

The documented concept design of the RSWs was therefore assessed to be in compliance with the R57 specification. The obligation for the Contractor following contract award was to design and construct all project RSWs including RW01 in accordance with R57 and R58. In this regard the Contractor was required to engage an engineering consultant to undertake external design of the RSWs whilst the internal design was being undertaken by a specialist contractor.

### 9 CONSTRUCTION STAGE ISSUES

During the construction the contractor reported that a minimum factor of safety of 1.35 as per R57 could not be attained for an RW01 section approximately between Station 675 and Station 705 by adopting the original reference design. The lowest computed FoS was about 1.20.

Review carried out by Hyder identified a number of factors that might contribute to the contractor not achieving a satisfactory FoS against global instability, namely: a) Browns slip restoration work (see below) altered the downslope profile below RW01; b) Design Alliance used previous survey profile, i.e. original down slope profile; and c) Use of relatively conservative design assumptions and parameters by the contractor.

Hyder undertook an independent slope stability assessment for RW01 at the cross sections of concern, and a summary of calculated FoS is presented in Table 6.

Table 6 Summary of calculated factors of safety at each station based on 2D Slope/W analysis

Station	660	675	685	695	700	710
Calculated FoS	1.41	1.27	1.20	1.22	1.24	1.37

An average FoS of the 30m wide block between Station 675 and Station 705 is calculated to be 1.24, based on the individual FoS of each of the four sections in Table 6. A FoS of 1.43 can be achieved when the side cohesion and friction resistance on both sides are considered. This implies when 3D effects are taken into account an increase in FoS of approximately 13% from the 2D analysis result, which is within lower end of the 3D enhancement of 10% to 50% found by other researchers such as A. Li et al (2009, 2010), Fredlund et al (2011) and Stark T (2012). This finding was presented to RMS at a workshop, and it was recognised that for a very long (>100m) and deep-seated (>10 m) slope to

fail, resulting from a lower FOS of 1.24 (average over 30 m) than required 1.35, the probability is very remote. This is particularly supported by the fact that it is unlikely for groundwater table to rise to the ground surface and to fully saturate the entire down slope given the steep terrain and measured standing water table in rock is well below the surface. To this end RMS accepted the minimum FOS of 1.24 (average, using 2D analysis) as a concession case for RW01. It was however emphasised that the 3D enhancement effect must be assessed on a case by case basis and should not be broadly applied to any of the 2D slope stability analytical results.

## 10 CONCLUSIONS

This paper has presented a case study of the use of site-won non-compliance fill material to R57 for construction of RSW walls by a systematic early planning, testing and design. It is found that there are limited guidelines available as to the permeability of the RSW fill when the fines content is close to 15%. The relaxation of fines passing of 75 microns up to 25% and 2.4 microns up to 7% were set for the RSW fill in a revised R57. This was coupled by: 1) the use of a lower pullout capacity of reinforcement by 10%; 2) the use of a friction angle of 30 degrees for the site-won fill; 3) an additional sacrificial allowance by 50%; and 4) provision of a groundwater management system including a clay liner above the RSW and a vertical drainage behind the RSW. These mitigation measures were devised to ensure a successful design of RSW using site-won material. The remedial works for the landslide in the vicinity of Brown's property access road were critical for the overall stability of the RSW wall - RW01. During construction due consideration of 3D effects in the slope stability analysis for the lower than standard R57 FoS of 1.35 was proved to be the best outcome for project.

It is suggested that further research be carried out to assess if the use of high fines content RSW fill material will yield satisfactory performance during its service life. Moderate proportion of fines such as this project case (up to 25% passing 75 micron and 7% passing 2.4 microns) may be considered for future projects with appropriate mitigation measures, including electrical and chemical limits testing as per BS8006. From a durability point of view R57 should be modified accordingly to include appropriate tests such as the organic content and potential acid sulphate soil to assess the corrosiveness of the fill material when the fines passing 75 microns is up to 15%.

At the time of writing this paper the westbound dual carriageway has been completed and the traffic switched onto the new traffic lanes being supported by the three RSWs. It has been reported that the RSWs have been performing within the expectation.

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## 12 DISCLAIMER

Neither the author/s, contributors, nor their respective organisations make any representation or warranty as to the accuracy, completeness or suitability or otherwise of the information contained in this paper and shall have no liability to any person in connection therewith.

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