Queensbury Tunnel

Phase 2: Technical Summary
Structure Number: HQU/3D

City of Bradford Metropolitan District Council

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1. Executive Summary

Queensbury Tunnel, Structure HQU 3D, is a disused former twin track rail tunnel situated between Bradford and Halifax. The tunnel runs directly beneath the town of Queensbury.

The tunnel is approximately 2300m in length, formed from masonry and brick arch with a span of some 8 metres and is situated up to 115m below the surface. The arch is 'gothic' in profile which, importantly, is a less structurally efficient profile when compared to a circular arch.

The tunnel was constructed in the 1870s but closed in the 1950s. There has been no significant maintenance of the tunnel or associated shafts and portals in the intervening period.

A series of tunnel examinations have been undertaken to further ascertain the current condition and likely extent of future tunnel repairs. These examinations have included: Visual and tactile surveys; 'Point Cloud' (three dimensional) profile survey; GPR (Ground Probing Radar) surveys; Intrusive surveys (cores and trial pits) and accompanying laboratory tests.

The examinations were not undertaken in or through the Highways England (the asset owner) prescribed 'exclusion zone'. A 305m length some mid-way within the tunnel. The exclusion zone is a length of cracked and deformed tunnel lining, including two partial collapses.

Data from the examinations have been used to undertake preliminary structural capacity assessments of the tunnel lining. These structural capacity checks, in conjunction with the examination data, were used to ascertain the likely extent and type of any remedial works required.

Key points of note from the surveys are as follows:

- A 'flattening' of the haunches (2'O'clock and 10 O'clock) through localised lengths of tunnel;
- The tactile survey confirmed circa 132m length of 'hollow'/delaminated lining (up to springing/axis level);
- Point cloud survey identified 435m length of out of profile lining (>100mm deflection);
- GPR survey identified that the lining was formed from material of different densities;
- Intrusive lining cores confirmed the presence of a hard facing stone on the intrados only, confirming the findings of the GPR survey;
- Visual surveys observed ongoing deterioration through developed longitudinal cracking in the brick lined lengths only;
- Visual surveys observed one circumferential crack in the stone masonry lining only;
- Visual survey confirmed that 99% of spalling occurred within the brick lined tunnel lengths;
- Visual survey confirmed increased mortar washout within the flooded length of tunnel.

The assessment of the tunnel lining has been further developed from the AECOM Baseline Report 60582061 REP001. This post examination structural assessment, based on yielded examination data and accompanying sensitivity analyses, has taken due cognisance of:

- Deformed and out of true tunnel profile;
- Varying lining compressive strength;
- Varying ground conditions and overburden (depth);
- Hydrostatic pressures (as a result of flooding of the tunnel and rapid draw down - pumping).

The post examination structural assessments indicated that the tunnel lining was:

- Likely to be within capacity where the tunnel was constructed through upper bound case (Sandstone, k=0.5). This was true for the tunnel at any depth.
- Overstressed where the tunnel was constructed through the lower bound case (Mudstone, k=1.5). This was true for the tunnel at any depth apart from the wholly lined stone masonry section with low cover (FE-P2-003).
- Within capacity where a full stone masonry lining of varying quality was present in the upper and lower bound cases for the section assessed.

The condition, performance and stability of the existing tunnel lining can be improved by undertaking a series of remedial works. These remedial works are:

- Pointing of joints between bricks/blocks (circa 1800 m^2);
- Replacement of localised fallen brick/block through sprayed concrete patch repairs (circa 510m^2 (420m^2 outside exclusion zone));
- Strengthening of the existing lining through installation of a new 'sprayed concrete' lining through deformed and cracked sections 495 m length (135m within the exclusion zone);
- Mass concrete backfill around an Armco culvert (or similar) through the partially collapsed length of tunnel 40 m length (not part of this study and within the exclusion zone);
- Shafts (not part of this study).

For reference, the estimated desk top study cost for the remedial works completed in Phase 1 report was £6,012,420.

The updated desk top study estimate for the updated Phase 2 remedial works is £6,912,050.

The key difference between Phase 1 & Phase 2 is the increased requirement for a concrete lining through the out of profile lining.

Importantly, the following additional examinations will be required in order to further understand the condition of the tunnel lining, shafts and geological setting.

- GPR survey in the southern half of the tunnel (sidewall, haunch and soffit);
- GPR survey in the northern half of the tunnel (haunch and soffit);
- Intrusive cores and associated laboratory testing through the tunnel lining, shaft lining and portals (min 40 cores);
- Intrusive cores to identity surrounding geological risks (40 cores inlc above);
- Point cloud survey within the exclusion zone;
- Shaft visual and tactile surveys;
- Portal visual and tactile surveys.

The desk top estimated cost for these surveys is £120K.

2. Introduction & Background

Queensbury Tunnel, structure HQU 3D, is a disused railway tunnel situated between Bradford and Halifax in West Yorkshire. The tunnel passes directly beneath the town of Queensbury.

The tunnel is approximately 2300m in length, formed from masonry and brick arch with a span of some 8 metres and is situated up to 115m below the surface.

The tunnel was constructed in the 1870s but closed in the 1950s.

Highways England (HE), through the Historic Railway Estate (HRE), currently has responsibility for the maintenance of the tunnel and the long-term management of the asset.

Jacobs Engineering (JE), on behalf of HE, has prepared a number of high-level engineering proposals for the abandonment or refurbishment of Queensbury Tunnel. Depending on the chosen solution, costs presented range in value from £3 million for abandonment to £36 million for refurbishment and reconstruction.

Queensbury Tunnel Society (QTS) has been formed with a view to maintaining the tunnel as an asset with the ultimate goal of reopening the tunnel as a multi-user trail. QTS has reviewed and critiqued the JE reports. QTS has prepared an independent estimate for the refurbishment of the tunnel at approximately £3 million.

AECOM have previously been appointed by the City of Bradford Metropolitan District Council (CBMDC) to provide an unbiased review of the JE and QTS documentation. AECOM considered that the JE option for full refurbishment were high, while those prepared by QTS were low. AECOM cost limit estimates for abandonment and refurbishment were broadly in the rage £8.5 million and £6 million respectively.

CBMDC now want to further understand whether they are able to adopt Queensbury Tunnel, including the long term maintenance and liabilities, from HE.

3. Scope of Works

AECOM has been appointed by the City of Bradford Metropolitan District Council (CBMDC) to undertake investigations and analysis to inform decisions on potential remediation proposals for the disused Queensbury Tunnel in West Yorkshire.

This scope of work constitutes Phase 2 of AECOM's work on the tunnel and builds upon a previous Phase 1 study by AECOM which reviewed historical data and previous work by others. Phase 1 of the works is described within the following document:

- 60564940-REP-001- Queensbury Tunnel Technical Oversight Phase 1 – Literature Review – Summary Technical Note

The Phase 2 works consist of a desktop study and baseline assessment, investigation and inspection works within the tunnel and subsequent assessment and interpretation. These works are described in the following documents, including this report:

- 60582061-REP001- Queensbury Tunnel, Phase 2: Desktop Study and Baseline Assessment
- 60582061-REP002- Queensbury Tunnel, Phase 2: Examination Survey Report
- 60582061-REP003- Queensbury Tunnel, Phase 2: Geophysical Investigation
- 60582061-REP004- Queensbury Tunnel, Phase 2: Intrusive Investigation Factual Report
- 60582061-REP005- Queensbury Tunnel, Phase 2: Post Examination Assessment Report
- **60582061-REP006- Queensbury Tunnel, Phase 2: Technical Summary**

A review of the previously prepared desk top estimate has also been undertaken.

Supporting documents and references used in the examination study are provided in Appendix A.

4. The Queensbury Tunnel

4.1 Location

Queensbury Tunnel runs directly beneath the town of Queensbury. Queensbury itself is located some five miles to the west of Bradford.

From the southernmost portal, at Strines Cutting near Holmfield, the tunnel runs some 2.3km in a north easterly direction, exiting near the former Queensbury Railway Station.

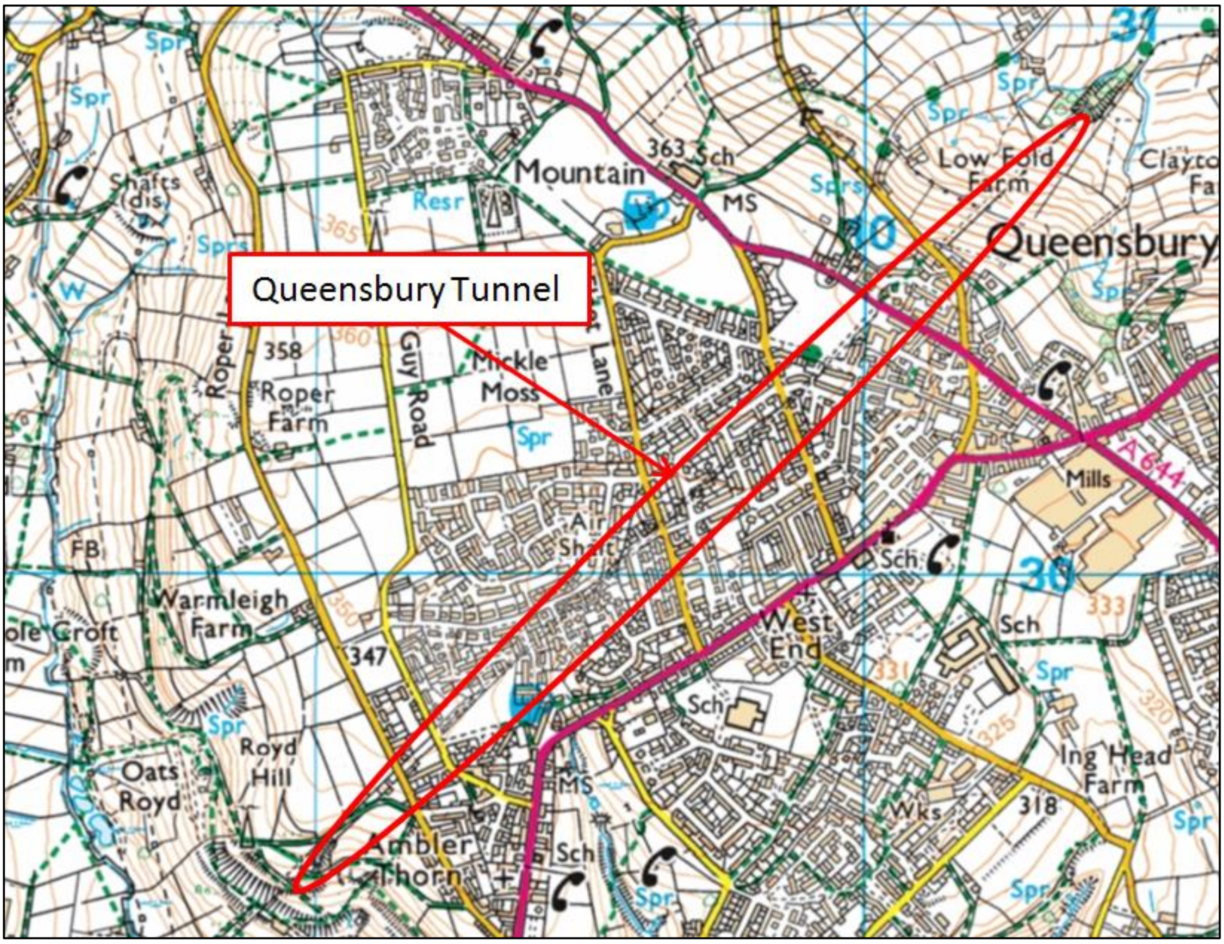


Figure 1: Queensbury Tunnel location plan

4.2 Tunnel form and structure

Queensbury Tunnel is some 2.3km in length. The tunnel rises, at a gradient of 1:100, from the southern portal to the northern portal. The tunnel is located up to 122m below ground level.

A total of eight on-line shafts were proposed to be constructed. These shafts would have originally been used to advance construction of the tunnel on several headings. Post construction, shafts would have been left open for ventilation.

Out of the eight shafts proposed only five were constructed. Of the three remaining shafts two were terminated some distance above the crown of the tunnel (due to high water flows). The remaining shaft was not commenced.

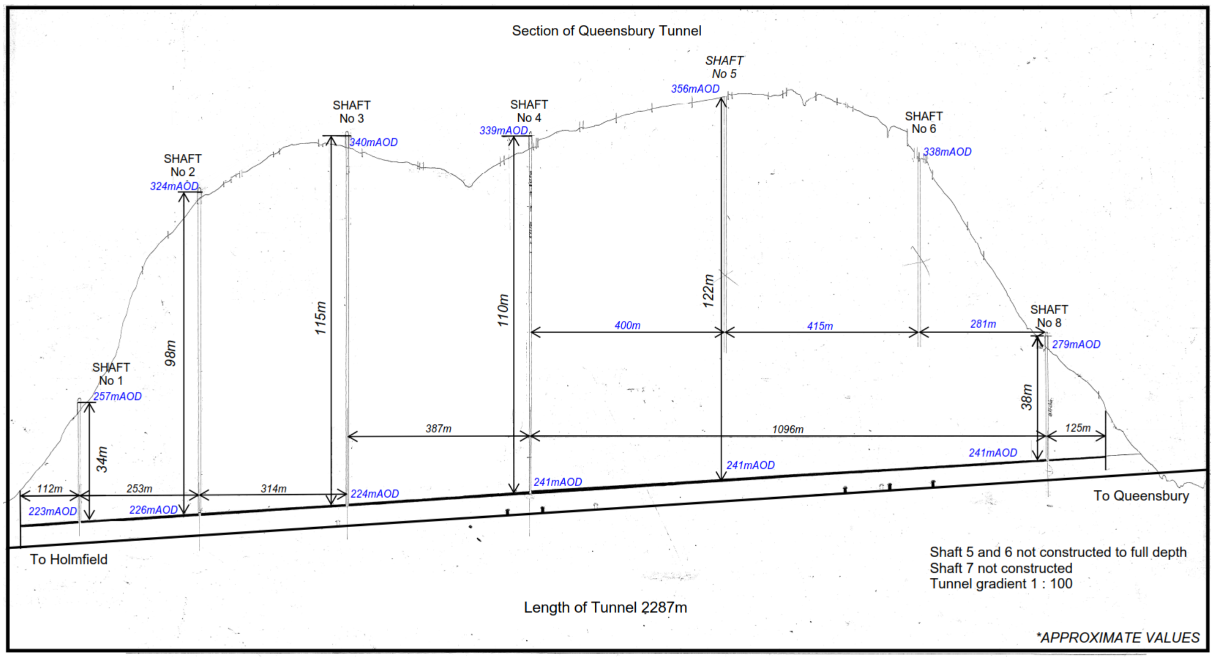


Figure 2: Longitudinal Section of Queensbury Tunnel

The tunnel is Gothic arch in profile (Figure 3) and 7.8m wide (26' 0") and 6.4m (21' 0") high (from ballast level). The tunnel is largely constructed from stone masonry sidewalls with a brickwork haunch and crown, some sections of the tunnel are formed of stone masonry only.

Lining thicknesses are recorded as 600mm (2' 0"). The ballast is recorded as being 600mm thick (2' 0") which sits above a central drain structure 1.2m (4' 0") wide. A dry lining is present at the extrados of the tunnel lining. The dry lining acts as a drainage layer to direct water flow around the lining and relieve external water pressures.

Experience shows that Gothic arch profiles are subject to increased stresses when compared to a circular arch.

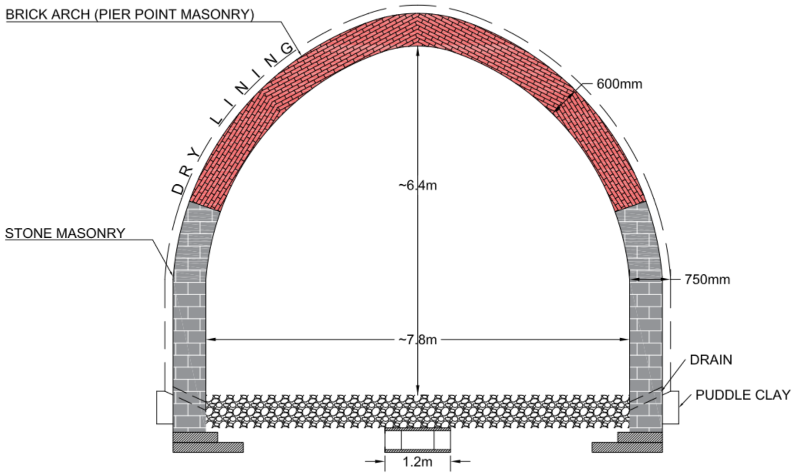


Figure 3: Idealised Tunnel Cross Section

4.3 Construction method

Queensbury tunnel was constructed by using drill and blast methods throughout.

Historic evidence indicates that advance rates were less than anticipated. Reduced advance rates were as a result of harder than expected rock and significant water ingress.

The use of explosive charges were, for the majority of the tunnel length, installed within shot holes that were drilled by hand. Advance rate recovery was only possible after a pneumatic shot hole drilling machine was used.

Key issues with drill and blast construction relate to the fracturing of rock outside of the excavated tunnel profile. It can be anticipated that this fractured ground is less competent than the surrounding rock mass. The fractured ground can lead to asymmetric loading on the tunnel lining and increased water flows.

4.4 Current environment

4.4.1 Flooding

Backfilling of the Strines Cutting has occurred at the southern end of the tunnel. This backfilling has resulted in a containment of ground and surface water within the cutting and into the tunnel. Water levels are historically known to have reached the full height of the tunnel.

Rapid drawdown of water within the tunnel, through pumping, will increase hydrostatic loading on the tunnel lining.

The impact of this imposed hydrostatic loaded is assessed later within this report.

4.4.2 Ventilation

Restricted ventilation within the tunnel occurs in two ways:

(i) Through a reduced free cross sectional area as a result of flooding; and,

(ii) Historic capping of shafts.

A reduced airflow with poor ventilation is a known factor for an increased rate of deterioration for underground structures.

4.5 Asset condition

HE have a full and complete schedule of all of the historic railway assets for which they are responsible.

It is understood that the HE schedule identifies risks posed to the general public, should any structure become unsound. HE have stated that the Queensbury Tunnel Structure (reference HQU 3D) poses the greatest risk to the public of all structures in their care.

The condition of the asset is well documented through historic surveys (referenced in Appendix A).

This report focuses on the extent of likely remedial works required, within the restrictions of the current examination, to extend the service life of the structure.

5. Delivery

5.1 Introduction

The following supporting AECOM documents have been produced as part of this commission:

- Desk Study and Baseline Assessment (Report Ref 60582061-REP001)
- Examination Report (Report Ref 60582061-REP002)
- Ground Probing Radar Survey (Report Ref 60582061-REP003)
- Intrusive Investigation (Report Ref 60582061-REP004)
- Post Examination Assessment (Report Ref 60582061-REP005)

This Summary Report (ref 60582061 REP 006) must be read in conjunction with these supporting technical documents.

A summary of the key objectives and accompanying findings are detailed in the following sections.

5.2 The Desk Study

5.2.1 Requirements

The desk study was undertaken to better understand the geological and hydrogeological setting, define geotechnical parameters, define tunnel lining material parameters and, as a result, understand the behaviour of the tunnel form and structural performance.

Understanding the likely and anticipated behaviour of the tunnel lining, in advance of the examination, would assist the engineering team.

5.2.2 Geological setting

The Queensbury Tunnel has been predicted to be sited within Sandstones and Mudstones of the Millstone Grit and Lower Coal Measures formations.

The geological groups are summarised as follows:

Table 1: Geological Groups within Queensbury Tunnel Site Area

Geological Sequence	Lithological Description	Age	Tunnel Location
Made Ground / Topsoil	Granular and cohesive constituents, fragments of brick, coal, ash and glass. Angular gravels of Mudstone and Sandstone.	Recent	Site Wide
Elland Flags Formation	Fine- to medium-grained flaggy to thickly bedded micaceous sandstone. The unit occurs as a number of sandstone leaves that are interbedded with dark micaceous and carbonaceous mudstone, locally containing thin dirty coals.	Carboniferous	Central
Pennie Lower Coal Measure	Interbedded grey mudstone, siltstone and pale grey sandstone, commonly with mudstones containing marine fossils in the lower part, and more numerous and thicker coal seams in the upper part.	Carboniferous	Site Wide
Millstone Grit	Fine- to very coarse-grained feldspathic sandstones, interbedded with grey siltstones and mudstones, with subordinate marine shaly mudstone, claystone, coals and seatearths.	Carboniferous	South-West

5.2.3 Baseline structural assessment

To understand the behaviour of the tunnel an initial assessment was completed. The purpose of this assessment was to inform the inspection teams of the likely failure mode and overstressed zones within the tunnel lining prior to undertaking the Phase 2 Investigative works.

Analyses were undertaken using Finite Element Modelling (FEM) software (Plaxis).

These FEM analyses were cross checked using empirical methods (Terzaghi and Deere) based on descriptions of rock mass characteristics. The lining was then checked using a plane frame structural analysis package (STRAP).

A full and detailed description of the analytical approach and findings is included in the AECOM Desk Study and Baseline Assessment Report.

5.2.4 Key findings

It is important to note that the exact geology at the tunnel horizon, by chainage, was not able to be determined from the geological records. This information can only be obtained from a full and detailed suite of intrusive investigations. These investigations are outside of the scope of this commission.

However, a thorough and detailed assessment of the tunnel lining and accompanying sensitivity analyses were undertaken. These assessments were based on historic reference data obtained from previously completed projects.

An example of the outputs from FEM analyses are shown below:

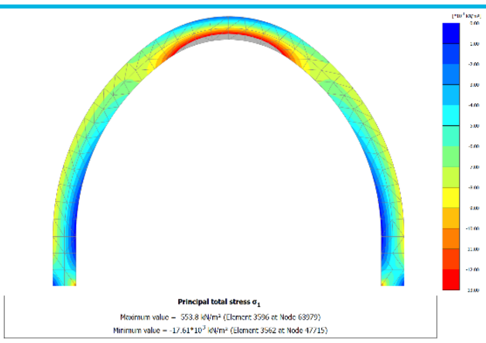
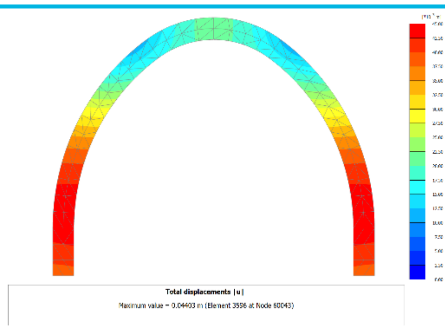
	Principal Total Stress Plot σ_1	Tunnel Lining Deformation Plot
Mudstone Minimum Cover K = 1.5 range		

Figure 4: Extract – Plaxis FE Analyses – Mudstone horizon – Low cover

Here, analyses indicate that the (brick) tunnel lining's capacity is partially exceeded within the soffit of the tunnel (grey zone).

The results of the analyses, using predicted Mudstone and Sandstone parameters in conjunction with tunnel lining material parameters are summarised as follows:

Table 2: Baseline Analysis Summary

Ground Material	Coefficient of Earth Pressure	Results
Mudstone	K = 0.5	Lining is within capacity.
	K = 1.5	Overstressing of the tunnel sidewalls and crown due to bending stresses.
Sandstone	K = 0.5	Lining is within capacity.
	K = 1.5	Overstressing of the tunnel sidewalls due to bending stresses.

5.3 The Examination

5.3.1 Requirements

The primary goal of examinations was to confirm previously documented visual survey data (completed by as referenced in Appendix A).

An exclusion zone exists for some 305 metres between Ch1250m and Ch1554m, (SM82 to SM102) with Ch0m at the northern portal. The exclusion zone has been previously defined by HE (the asset owner) due to the presence of two partial collapses of the tunnel lining. This tunnel length has been excluded from the examination.

5.3.2 Visual and tactile surveys

The visual and tactile surveys were undertaken to develop a detailed engineering understanding as a result of observing:

- Cracked lengths of lining – their orientation, extent and 'lipping'
- Bulged and deformed sections of lining – location and extent on the tunnel intrados
- Water ingress – through the tunnel lining and at shaft locations.
- Mortar loss, loose and fallen brick and blockwork – as a result of water ingress or overstressing.
- Lengths of tunnel unaffected by defects.

A full and detailed account of the survey is included in the accompanying AECOM Examination report ref 60582061-REP002.

5.3.3 Point Cloud Survey

The internal profile (intrados) of the tunnel lining was required in order to:

- Confirm the spatial arrangement and dimensions of the tunnel profile as compared to record drawings
- Determine and measure deflections and deformations of the tunnel linings precisely
- Enable subsequent structural assessments to be completed using deformed lining profiles

A three dimensional 'point cloud' survey was undertaken in lieu of two dimensional laser surveys at specific chainages. The point cloud survey is capable of being interrogated at an infinite number of locations and cross sections and yields the maximum amount of data for assessment.

A typical extract from the model, in which individual bricks/blocks can be interrogated, is shown in Figure 5.

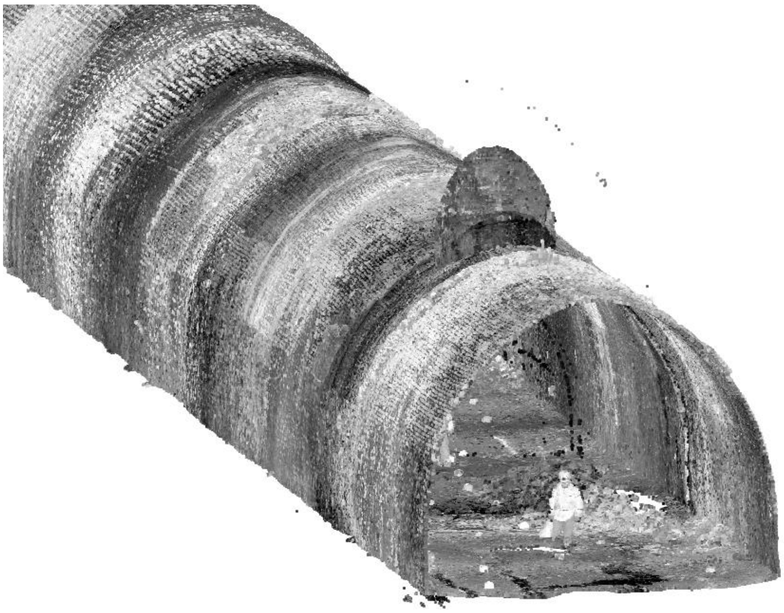


Figure 5: Point Cloud Survey Extract CH 80m facing northwards

A full and detailed account of the survey is included in the accompanying AECOM Examination report ref 60582061-REP002.

5.3.4 Key findings

The visual and intrusive surveys confirmed a further deterioration in the tunnel lining since when compared to available data referenced in Appendix A.

The current observed features are summarised below.

Table 3: Summary of tunnel defects (less exclusion zone)

Chainage	Section Marker	Arch material	Spalling (m^2)	Loose/missing bricks (m^2)	Open Joints (m^2)	Water Ingress
Ch0-Ch77m	0 to 5	Stone	2	9	60	Dry
Ch77 –Ch190m	5 to 12	Brick	30	126	134	Water Running
Ch190-Ch198m	12 to 13	Stone	0	0	125	Water Dripping
CH198-Ch765m	13 to 50	Brick	256	184	95	Water Dripping
CH765-CH1250m	50 -82	Brick	383	20	228	Damp
CH1401- CH1554m	102 to 104	Brick	10	0	14	Dry
CH1605-CH1643m	104 to 107	Stone	2	3	335	Water Running
CH1643-CH1932	107 to 126	Brick	127	28	197	Damp
CH1932-CH1955m	126 to 127	Stone	0	0	133	Water Running
CH1955-CH2149m	127 to 142	Brick	327	40	595	Water Dripping
CH2149-CH2288m	142 to 150	Stone	2	11	0	Damp
	0 to 82, 102 to 150	**TOTAL**	**1140**	**420**	**1920**	

A detailed summary of deformations and cracking along the length of the tunnel are:

Table 4: Summary of deformations and cracking (less exclusion zone).

Chainage	Section Marker	Lining Type	Out of Profile Section (m)	Observed Deformation	Visual and tactile examination observations
CH58–CH72	4-5	Stone Masonry	13	Asymmetrical bulging of up haunch	Open jointing/missing bricks
CH76-CH86	5-6	Brick	10	Flattening of haunches	Missing brickwork in both haunches
CH289-CH310	19-20	Brick	21	Flattening of haunches	Missing brickwork in both haunches
CH502- CH548	33-34	Brick	46	Flattening of haunches Localised bulging of down sidewall.	Longitudinal hinge crack on both haunches. Drummy brickwork
CH690-CH700	45-46	Brick	10	Asymmetrical bulging of down haunch	Longitudinal crack on down haunch. Missing brickwork on down haunch.
CH777-CH791	51-52	Brick	14	Flattening of haunches	Longitudinal hinge crack on both haunches
CH1010-CH1020	66-67	Brick	10	Bulging of down side wall	Drummy brickwork
CH1030-CH1051	68-69	Brick	21	Bulging of down side wall	Drummy brickwork
CH1082-CH1257	71-82	Brick	175	Localised bulging	Drummy brickwork Longitudinal hinge crack
CH1605-CH1643	105-106	Stone	15	Asymmetrical bulging of up haunch	Drummy brickwork
CH1874-CH1890	123-124	Brick	10	Asymmetrical bulging of up haunch	Longitudinal hinge crack
CH1890-CH1955	124-127	Stone	45	Bulging of up sidewall	Collapsed refuge
CH1995-CH2040	127-130	Brick	45	Flattening of haunches	Longitudinal hinge crack on both haunches
TOTAL			**435m**		

Deformations and cracking and bulging of the tunnel lining can occur through:

- Overstressing of the tunnel lining from ground loading – symmetrical or asymmetrical;
- A shearing of the tunnel lining from asymmetrical ground loading.

5.4 The Ground Probing Radar Survey

5.4.1 Requirements

Ground Probing Radar (GPR) is a technique by which variations in the tunnel lining can be identified. Two separate frequencies are used in order to differentiate between near surface features and those at depth.

Longitudinal GPR profiles were undertaken at heights of 1.5m and 3.0m along the tunnel sidewalls.

The GPR survey was undertaken in order to identify:

- The tunnel lining thickness;
- Separation between the leaves of brick or stone masonry;
- Voiding behind the tunnel lining (at the extrados);

- Micro voiding (fracturing) of the rock mass.

The GPR survey was undertaken on stone masonry and brick sections of lining.

A full and detailed account of the GPR survey is included in AECOM report ref 60582061-REP003.

5.4.2 Key findings

The following features were identified form GPR data:

- The tunnel lining thickness is in line with historic record drawings. The lining thickness is circa 2' or 0.6m;
- Highly reflective boundary some 0.25m and 0.35m behind the intrados of the tunnel lining in the stone masonry and brick lined sections respectively;
- Micro-voiding within the rock mass – most likely as a result of the use of explosives;
- Limited or no apparent voiding behind the extrados.

The strong reflective boundary at 0.25m (mean value) within the stone masonry tunnel lining sidewall indicates a difference in either or both of:

- Material quality and form (presence of a competent sandstone facing with less competent material behind);
- Material placement (structured placement of the sandstone facing to a regular pattern with unstructured placement of lining materials behind the facing stone).

The reflective boundary at 0.35m (mean value) within the brick tunnel lining indicates a difference in either or both of:

- Material quality and form (presence of more competent brick with less competent or degraded material behind).

Variations in lining quality and mean thicknesses are used in the post examination assessment AECOM Report Reference 60582061-REP005.

5.5 The Intrusive Investigations

5.5.1 Requirements

Two types of investigations are required:

- Cores;
- Trial pits.

Coring was undertaken through the sidewalls of the tunnel lining. These cores are used to identify:

- Lining thickness;
- Visual understanding of lining form and quality;
- Provide samples for laboratory testing.

The following key laboratory tests were required for stone masonry and brick samples:

- Compressive Strength (N/mm^2);
- Apparent Density (kg/m^3);
- Direct Tensile Strength (N/mm^2);
- Modulus of Elasticity, E (Mpa);
- Poisson's Ratio.

The laboratory testing provides further data for use in the structural assessment of the tunnel lining. In particular, the laboratory test data is used to confirm, or otherwise, assumptions used in the baseline structural assessments - AECOM Report 60582061-REP001 refers.

Any completed trial pits are undertaken to confirm the presence or otherwise, of a structural invert beneath ballast level. The presence of any invert will impact the behaviour of the tunnel lining and corresponding structural assessment.

5.5.2 Key findings

The tunnel lining was confirmed as being some 2' (0.6m) in thickness. Minimum observed and interpolated lining thickness (five leaves of brick) is 0.55m.

Sample cores confirmed the presence of a competent facing stone with varying material behind.

The facing stone is sandstone with the remaining material, which forms the body of the lining, being formed from mudstone and brick.

A summary of material properties and parameters of the tunnel lining are presented in Table 5.

Table 5: Intrusive test data

Sample reference number	Lining thickness (mm)	Facing stone thickness (mm)	Apparent Density (kg/m^3)	Compressive Strength (N/mm^2)	Direct Tensile Strength (N/mm^2)	Modulus of Elasticity (E)	Poisson's Ratio
C0001	840	340	2360	92.8	4.7	17200	0.07
C0002	460	460	2320	71.6	4.2	16000	0.06
C0003	860	215	2360	77.4	3.6	13800	0.06
C0004	-	-	-	104.5	-	-	-
Brick 1	-	-	2140	9.2	-	-	-
Brick 2	-	-	2180*	15.1	-	-	-
Brick 3	-	-	2030*	11.8	-	-	-
Block	-	-	2310*	72.1	1.7	7600	0.004

* Saturated Density

The trial pit confirmed that the tunnel did not have structural invert.

A full and detailed description of the intrusive and laboratory tests are included in AECOM Report ref 60582061-REP004.

5.6 The Post Examination Assessment

5.6.1 Requirements

Data yielded from each of the visual & tactile, point cloud, GPR and intrusive examinations has been used to further develop the baseline structural assessment. These are presented in the Post Examination Assessment report (AECOM Report ref 60582061-REP005).

The results of the post examination analyses are used to confirm, or otherwise, the baseline predicted structural behaviour of the tunnel lining.

In turn, the post examination assessment is used to further develop any required remediation measures. In particular, any requirement for an additional internal concrete lining and the form of that concrete lining.

5.6.2 Tunnel lining assessment

Analyses were undertaken using Finite Element Modelling (FEM) software (Plaxis). This was used to assess the tunnel structure in its existing condition based on the findings of the examination undertaken.

An SCL remediation option was then assessed using empirical methods (Terzaghi and Deere) accompanied by use of a plane frame structural software (STRAP).

Sensitivity analyses were performed in order to take due cognisance of yielded examination data. In particular, this included:

- Amendment of compressive strength values for stone masonry elements of the tunnel lining;
- Confirmation, from laboratory testing, that a 'mean' value for compressive strength of the brick lined elements of the tunnel lining was acceptable;
- Use of 'as surveyed' tunnel lining profiles;
- Reduction of tunnel lining thickness from 0.6m to 0.25m in stone masonry lined sections only;
- Reduction of tunnel lining thickness from 0.6m to 0.55m in brick lined sections only;

It is important to note that:

- The geological conditions through which the tunnel passes were not determined as part of this examination. As such, a series of sensitivity analyses, using differing geotechnical parameters, were undertaken to understand how the tunnel lining behaved within the predicted geologies. This was in line with the baseline assessment and a lower bound case of a mudstone horizon with a K of 1.5 was adopted. A upper bound case of a sandstone horizon with a K of 0.5 was also assessed;
- Performance of the tunnel lining, due to the loss of mortar, was not assessed;
- Performance of the tunnel lining at shaft interfaces were not assessed;
- Mortar quality was not taken into account;
- Cracked sections of lining (possible hinge formation) were not assessed within this study.

5.6.3 Key findings

5.6.3.1 Existing condition

Example of the outputs from FEM analyses are shown below:

Principal Total Stress Plot σ_1 | **Tunnel Lining Deformation Plot**

Mudstone

SM77.5

Depth 115

K = 1.5

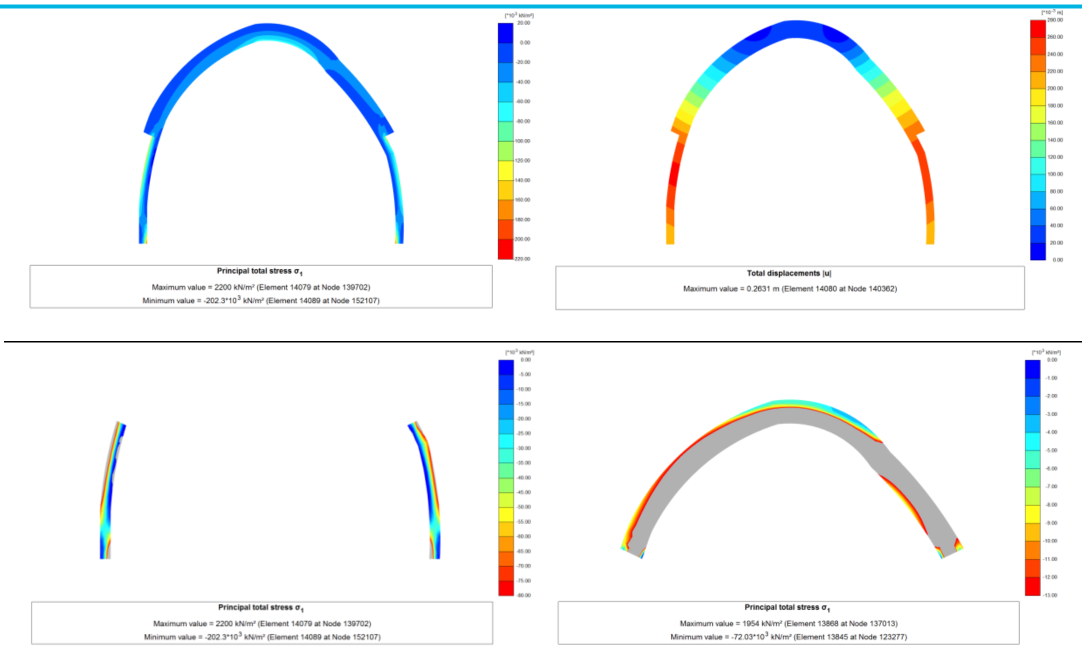


Figure 6: Extract – Plaxis FE Analyses – Mudstone Horizon – Deformed Profile SM77.5

In the above example, analyses indicate that, when considering existing deformations and the refinement to the tunnel sidewall lining properties, the sidewall show signs of high compressive stresses on the extrados and localised tensile stresses on the intrados. This is still considered to be within capacity, albeit with highly stressed zones. The crown of the tunnel shows that the compressive stresses are far greater that the assumed compressive capacity of the brick lining. It is therefore considered to be out of capacity.

The results of the analyses, using predicted Mudstone and Sandstone parameters in conjunction with tunnel lining material parameters are summarised as follows:

Table 6: Post Examination Analysis Summary

Model reference	Approximate Section Marker	Cover	Load Case	Results
FE-P2-001	Idealised Section (Deep)	122	Mudstone K = 1.5	Overstressing of the tunnel sidewalls due to high compressive stresses at the tunnel extrados. Tunnel crown is overstressed due to compressive stresses.
FE-P2-002	Idealised Section (Shallow)	34	Sandstone K = 0.5	Lining is within capacity.
FE-P2-003	4	27	Mudstone K = 1.5	Lining is within capacity.
FE-P2-004	4	27	Sandstone K = 0.5	Lining is within capacity.
FE-P2-005	77.5	115	Mudstone K = 1.5	Overstressing of the tunnel sidewalls due to high compressive stresses at the tunnel extrados and some localised tensile stress at the intrados. Tunnel crown overstressed due to compressive stresses.
FE-P2-006	77.5	115	Sandstone K = 0.5	Sidewall is within capacity. Tunnel crown is locally overstressed due compressive stresses
FE-P2-007	120	108	Mudstone K = 1.5	Overstressing of the tunnel sidewalls due to high compressive stresses at the tunnel extrados. Tunnel crown is overstressed due to compressive stresses.
FE-P2-008	120	108	Sandstone K = 0.5	Sidewall is within capacity. Tunnel crown is locally overstressed due compressive stresses

5.6.3.2 Concrete Lined Remediation

The deformed profile taken at SM77.5 was reassessed using STRAP with the required new inner concrete lining. A typical Sprayed Concrete Lined (SCL) thickness of 300mm was used in analyses.

The results of the analyses indicate A 300mm sprayed concrete lining is deemed sufficient when considered to act as a composite liner in conjunction with the existing brick lining. The composite liner is envisaged to be formed of the brickwork/stone masonry and SCL through a frictional interface and pins installed which are encompassed by the SCL concrete. This approach is considered to utilise the existing lining and minimise the thickness of the SCL. It is considered that at set intervals strips of drainage layers will be installed to allow the drainage of any built up ground water so as to not additionally load the tunnel.

Greater structural efficiency may be achieved through placement of a new concrete lining with a more circular profile. Any such assessments fall outside the scope of this examination assessment and must be undertaken as part of any future detailed remediation design.

The post examination analyses broadly confirmed the findings, as presented, in the baseline assessment (AECOM Report Ref 60582061-REP001).

The post examination assessment indicated that:

- The tunnel lining was likely to be within capacity where the tunnel was constructed through upper bound case (Sandstone, k=0.5). This was true for the tunnel at any depth. The improvement over and above the baseline was due to the improved compressive strengths of the sandstone block over brick lining.
- The tunnel lining was overstressed where the tunnel was constructed through the lower bound case (Mudstone, k=1.5). This was true for the tunnel at any depth apart from the wholly lined stone masonry section with low cover (FE-P2-003). The results showed a marginal improvement over and above the baseline was due to the improved compressive strengths of the sandstone block over brick lining.

In addition, the post examination assessment concluded that:

- Placement of a new inner concrete lining of minimum 300mm thickness would be suitable to carry long term loading if considered to act a composite liner in conjunction with the existing brick lining. This is an initial indication of the strengthen requirements and will be subject to a detailed evaluation and design.
- Within the limitation of this study, we were unable to model the effects, for the applied hydrostatic loading on the tunnel for the flooding and drawdown. However, as a result of flooding and drawdown the following effects have been observed from the examination:
    - Missing mortar from masonry and brick joints throughout the flooded section resulting in loose bricks and missing bricks;
    - Accelerated deterioration of the tunnel lining;
    - Draining and undraining of ground surrounding tunnel lining causing potential consolidation behind the lining;
    - Large volumes of debris dragged into the tunnel through flooding.
    - Particular issues arise at the deformed section of lining and partially collapsed refuge at Ch1936 (SM 127).

A full and detailed assessment of the tunnel lining is included in AECOM Report ref 60582061-REP005.

6. Remedial works proposals

The remedial work form remains in line with those suggested within the AECOM Phase 1 Technical Oversight Report reference 60564940-REP-001. These are summarised below, for the benefit of the reader.

6.1 Local repair

Local repairs and associated remediation measures are broadly categorised into either:

- Replacement of lost mortar at joints between brick and stone masonry. Pressure pointing would be considered suitable to make good mortar loss.
- Replacement of fallen leaves of brick and stone masonry. Infill of lost masonry is through placement of sprayed concrete with connection dowels is considered suitable.

6.2 Relining

6.2.1 Concrete Lining

Those lengths of tunnel that are deformed or cracked must, as a minimum, be strengthened through the placement of a new inner concrete lining.

The strengthening would most likely be formed from steel fibre reinforced (sfr) sprayed concrete lining (SCL). Alternatively, a cast in place lining could be used.

The concrete lining must extend around the entire intrados of the tunnel lining to ballast level.

The post examination structural assessment indicates that a minimum thickness of 300mm is required. This has not been refined to develop a more ‘efficient’ profile through deformed lengths of lining. It would be recommended that this exercise is completed during further design phases. The thickness is dependent on the new and existing lining acting in a composite manner (i.e. together).

Certainly, deformations of the tunnel lining will impact the structural capacity. The extent of SCL arch remediation required has been determined based on existing lining deflections of greater than 100mm.

Importantly, the full extent of the SCL arch strengthening must be verified through further intrusive and non-intrusive surveys. Key determinations will include potential separation between leaves of brick/block, voiding behind the tunnel lining and material properties of the tunnel lining and surrounding geology.

The lengths of SCL arch strengthening are shown, in conjunction with recorded defects, on the survey drawing enclosed within Appendix D.

The extent of SCL arch remediation within the exclusion zone has been extracted from the QTS Asset or Liability Report. The extent of the SCL arch repair and indeed, other remedial works within the exclusion zone, will need to be determined through further detailed examinations.

6.2.2 Armco culvert and backfill surround (exclusion zone)

A cast concrete lining surrounding a steel culvert is considered a suitable method of repair through partially collapsed lengths of tunnel.

The extent of the cast lining repair has not been assessed as part of this study, as access into the exclusion zone was not possible.

6.3 Examination Limitations

6.3.1 Portals

Examination of portal structures was excluded from this study.

6.3.2 Shafts

Examination of shaft structures was excluded from this study.

6.3.3 Drainage

Examination of track bed drainage was excluded from this study.

6.3.4 Ground Improvement

Ground improvement is a means by which the physical properties of the ground surrounding the tunnel lining is improved.

Ground is improved through grouting of the surrounding rock mass. This grouting endeavours to infill voids, close cracks and fissures and reduce water ingress through the sealing of water paths.

The extent of any required ground improvement was excluded from this study. This can only be ascertained following further intrusive testing of the surrounding geology and accompanying laboratory testing.

6.3.5 Grouting – Tunnel Lining

The separation of any leaves (rings) of brick or stone masonry will reduce the structural performance of any tunnel lining.

These hidden voids can be closed through the injection of grout, at low pressure, to infill between any separated leaves of brick/block.

The extent of any grouting of the tunnel lining has not been assessed as part of this study. The extent can only be determined following a detailed series of GPR surveys and focused intrusive tests (lining cores).

6.4 Summary of remedial works

The quantity of estimated remedial works has been developed from those cited within the AECOM Phase 1 Technical Oversight Report. These have been updated to reflect the latest examination findings. Where elements of the tunnel (the exclusion zone) and shafts have not been surveyed, baseline estimates remain unchanged.

Table 7: Remedial works summary

Remedial work	Quantity (as Option 4a baseline)	Quantity (post examination assessment)
Pointing (Tunnel)	1200 (m^2)	1800 (m^2)
Pointing (Shafts)	950 (m^2)	950 [1] (m^2)
Brickwork repair	40 (m^2)	130 (m^2)
Brickwork replacement	210 (m^2)	240 (m^2)
Stonework replacement	115 (m^2)	35 [2] (m^2)
SCL patch repair (100mm deep)	510 (m^2)	510 [3] (m^2)
SCL full lining circumferential lining (deformed lining lengths)	210 (m)	495 (m)
ARMCO Backfill	40 (m)	40 [4] (m)
Grouting (between brick leaves and external voids)	400 (m^3)	400 [5] (m^3)

[1] No change from original estimate. Shafts not surveyed.

[2] Within surveyed lengths only.

[3] 420m^2 within surveyed lengths only. Total includes estimated value from within the exclusion zone

[4] No change from original estimate. Exclusion zone not surveyed.

[5] No change from original estimate. Further field testing required.

6.5 Risk assessment

An updated (Jacobs Engineering) summary risk assessment is included within Appendix C.

7. Remediation estimate

A comparison of the estimated remediation cost limits are summarised below.

It is imperative that the reader recognises that this is a high level desk top estimate only.

The desk top estimate has been supported through AECOM's own knowledge, the ongoing HS2 and Hinkley Point C projects, together with the previous additional helpful support of the following Civil Engineering and Tunnelling Contractors: Dyer & Butler Ltd; Shotcrete Ltd and Murphy Ltd.

The costs presented are not whole-life costs and do not take into account ancillaries for safe operation and maintenance.

The baseline remediation costs are as previously identified as 'Option 4a' within the AECOM Phase 1 Technical Appraisal Report (ref 60564940-REP-01).

Post examination remediation assessment based on new examination data and corresponding structural analyses is included as a comparison.

Table 8: Summary of Cost Limits

Item	AECOM Cost Limit (Jan 2018)	JACOBS Cost Limit (2016)	QTS Estimate (2017)	Comment
Phase 1: Baseline Remediation Assessment	**£6,012,419**	£35,381,398	£2,810,000	Differing repair methodologies for AECOM (QTS) / JE. Costs vary.
	AECOM Cost Limit (Oct 2018)			**Comment**
Phase 2: Post Examination Remediation Assessment	**£6,912,050**			Methodology remains largely unchanged from previous AECOM (QTS) proposals. Quantities differ.

The breakdown of these high level desk top cost plans are included in Appendix C.

Comments on these headline costs are as follows:

Costs have not been adjusted for inflation. Baseline values have been used as previously used in Option 4a.

Civil Engineering Works: The exclusion zone was not surveyed as part of these works. Costs within the exclusion zone remain unchanged from Option 4a.

Civil Engineering Works: Estimates for Repointing, brickwork and Stonework Repair and Replacement and SCL patching have been amended, where appropriate, to reflect the current examination. These estimated values may be revised further following a full tactile survey and examination of the exclusion zone.

Civil Engineering Works: SCL full arch. This value has been increased in line with data yielded from the examinations.

Civil Engineering Works: Grouting estimate remains unchanged. Further GPR and intrusive cores are required to determine grouting estimates.

Civil Engineering Works: Repointing values remains unchanged. Surveys required to confirm assumption. Strengthening works may also be required. These values are excluded.

General Items: Based on a 44 week construction programme. As previous option 4a. Costs are largely time dependant. A cost of £40 thousand per week is considered to be within reasonable bounds.

Accommodation: This is a fixed set-up item, not time related and considered to be within reasonable bounds. As previous option 4a.

Facilitating: This is assumed to cover formation of access for the tunnel and shafts, together with the works compound and temporary utilities. Facilitation as previous option 4a.

Design Fee: This has been revised and reduced from 15% previously to 10% of the construction estimate. This is felt to be within reasonable bounds, depending on services required.

Development Costs: It is assumed that this covers the full suite of investigative works including intrusive and non-intrusive tests plus further searches/studies/impact assessments. This does not include for analytical assessments of remedial works designs.

Risks: An addition of 35% is acceptable and in line with works at this preliminary stage. This is reduced from the previous figure of 40% due to additional information being obtained.

Optimism, Inflation and VAT: These are all excluded. This is noted, considered acceptable and in line with the previous option 4a.

8. Conclusions & Recommendations

This completed investigations and analysis have been able to further inform and confirm the type and extent of the required remedial measures for the disused Queensbury Tunnel in West Yorkshire.

The key findings from the surveys included:

- Ongoing 'live' deformation and cracking of the tunnel lining within the crown was observed;
- Differing material types and/or placement within the stone masonry lengths of arch were noted in GPR and intrusive cores;
- Out of profile length of tunnel as a result of the point cloud survey.

The remedial works required include repair through:

- Pointing and localised brick/stone replacement;
- SCL patch repair;
- SCL full arch; and,
- ARMCO arch and backfill.

For reference, the estimated desk top study cost for the remedial works completed in Phase 1 report was £6,012,420.

The updated desk top study estimate for the updated Phase 2 remedial works is £6,912,050.

The key difference between Phase 1 & Phase 2 is the increased requirement for a concrete lining through the out of profile lining.

The extent of ground improvement, water management and ecological requirements have not been assessed as part of this study.

The following additional examinations will be required in order to further understand the condition of the tunnel lining, shafts and geological setting.

- GPR survey in the southern half of the tunnel (sidewall, haunch and soffit);
- GPR survey in the northern half of the tunnel (haunch and soffit);
- Intrusive cores and associated laboratory testing through the tunnel lining, shaft lining and portals (min 40 cores);
- Intrusive cores to identity surrounding geological risks (40 cores inlc above);
- Point cloud survey within the exclusion zone;
- Shaft visual and tactile surveys;
- Portal visual and tactile surveys.

The estimated cost for these surveys is £120K.

Appendix A - References

AECOM Queensbury Tunnel. Phase 1: Technical Oversight Report

AECOM Queensbury Tunnel. Phase 2: Desktop study and Baseline Tunnel Assessment Report

AECOM Queensbury Tunnel. Phase 2: Examination Report

AECOM Queensbury tunnel. Phase 2: GPR Report

AECOM Queensbury Tunnel. Phase 2: Intrusive Investigation Report

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Appendix B - AECOM High Level Desktop Cost Plan

The high level desktop cost plan for the **baseline option**, the previous Option 4a, is given in Table B1.

Table B1. Baseline High Level Desktop Cost Plan

Item	High Level Cost
Civil Engineering Works	
Tunnel Repair Works	
Repointing	£78,000
Brickwork & Stonework Repair and Replacement	£47,450
SCL Patching and Dowels	£104,550
SCL Full Arch Repair and Rock Bolts	£817,950
Repair of Collapsed Sections	£343,380
Grouting Voids Behind the Lining	£119,340
Sub-Total	**£1,510,670**
Shaft Repair Works	
Repointing	£92,630
Sub-Total	**£92,630**
General Items	
General Items Allowance	£1,760,000
Facilitating works	£82,500
Accommodation works	£49,500
Sub-Total	**£1,892,000**
Total (Civil Engineering Works)	**£3,495,291**
Project / Design Team Fees	
Detailed Design Allowance	£524,293
Total (Project / Design Team Fees)	**£524,293**
Development / Project Costs	
Development / Project Costs Allowance	£275,000
Total (Development / Project Costs)	**£275,000**
Risk / Optimism Bias	
Risk Allowance	£1,717,834
Optimism Bias Allowance	Excluded
Total (Risk / Optimism Bias)	**£1,717,834**
Inflation	
Inflation Allowance	Excluded
Total (Inflation)	**Excluded**
VAT	
VAT Allowance	Excluded
Total (VAT)	**Excluded**
COST LIMIT (BASELINE OPTION)	**£6,012,420**

The high level desktop cost plan for the **post examination option** is given in Table B2.

Table B2. Post Examination High Level Desktop Cost Plan

Item	High Level Cost
Civil Engineering Works	
Tunnel Repair Works	
Repointing	£117,000
Brickwork & Stonework Repair and Replacement	£52,650
SCL Patching and Dowels	£104,550
SCL Full Arch Repair and Rock Bolts	£1,928,025
Repair of Collapsed Sections	£343,380
Grouting Voids Behind the Lining	£119,340
Sub-Total	**£2,664,945**
Shaft Repair Works	
Repointing	£92,630
Sub-Total	**£92,630**
General Items	
General Items Allowance	£1,760,000
Facilitating works	£82,500
Accommodation works	£49,500
Sub-Total	**£1,892,000**
Total (Civil Engineering Works)	**£4,645,575**
Project / Design Team Fees	
Detailed Design Allowance	£325,470
Total (Project / Design Team Fees)	**£325,470**
Development / Project Costs	
Development / Project Costs Allowance	£145,000
Total (Development / Project Costs)	**£145,000**
Risk / Optimism Bias	
Risk Allowance	£1,792,010
Optimism Bias Allowance	Excluded
Total (Risk / Optimism Bias)	**£1,792,010**
Inflation	
Inflation Allowance	Excluded
Total (Inflation)	**Excluded**
VAT	
VAT Allowance	Excluded
Total (VAT)	**Excluded**
COST LIMIT (POST EXAMINATION OPTION)	**£6,912,050**

Appendix C - Risk Assessment

Project Risk Assessment

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Risk No	Hazard/Risk Description	Cause	Before Mitigation			Consequence	Mitigation/Control Measures/Opportunity/Persons Responsible Client (CL), Designer (D), Contractor (CO)	Post Mitigation		
			Impact	Prob	Risk			Impact	Prob	Risk
Queensbury Tunnel: Generic and specific Hazards/Risks on the Tunnel & Shafts										
1	Further deterioration of the tunnel lining sections - instability.	Surrounding geological and hydrogeological conditions including: - Coal seam(s) - Fractured ground surrounding the tunnel (from drill & blast operations) - Groundwater - Voids	5	5	25	Further lining deterioration as a result of asymmetric ground loading. Asymmetric loads could ultimately result in a tunnel collapse. Tunnel collapse will increase the remedial works duration, cost and related construction and third party hazards. Further collapse in the tunnel may result in serious injury or even death. Third party claims could also result.	Access to the Tunnel during the decision making period to be prevented at all times for all members of the public and restricted for essential personnel. Additional investigative works required to include: - Point cloud survey through exclusion zone - Ground probing radar (GPR) survey to verify voids behind the lining and separation of brick leaves - Intrusive cores through the tunnel lining and into the surrounding geology to confirm lining and ground parameters Undertake structural assessment of lining. Install remedial strengthening measures as required.	5	1	5
2	Further deterioration of the Tunnel Lining sections - instability	Tunnel age in conjunction with lack of ongoing maintenance of the tunnel (shaft and portals) lining. Resulting in the following defects, including: - Spalling - Falling brick/blockwork - Mortar loss & open joints - Deformation	5	5	25	Reduced tunnel lining thickness. Increased lining stresses due to reduced tunnel lining thickness. Increased stress will be drivers for further lining collapses. Further collapse in the tunnel may result in serious injury or even death. Third party claims could also result.	Access to the tunnel during the decision making period to be prevented at all times for all members of the public and restricted for essential personnel. Additional investigative works required to include: - Point cloud survey through exclusion zone - Ground probing radar (GPR) survey to verify voids behind the lining and separation of brick leaves - Intrusive cores through the tunnel lining and into the surrounding geology to confirm lining and ground parameters Undertake structural assessment of lining. Install remedial strengthening measures as required. Install remedial strengthening measures as required.	5	1	5
3	Flooding at the south end of the tunnel (Holmfield portal)	Historic infilling of Strines Cutting	5	5	25	Infilling of Strines Cutting has resulted in flooding of the south end of the tunnel. Due to the flooding the lining in the area has further deteriorated (mortar in between the brick/masonry joints has been washed away). Mortar loss (reduced section effectiveness) will result in overstressing. Increased stresses are a driver for lining collapses.	A pumping station has been designed and installed. Negotiations with land owner are ongoing to allow for the system's installation. Dewatering to be undertaken at an acceptable rate to reduce the risk of destabilising the tunnel lining during dewatering. The pumping system needs to be maintained and operated on a continual basis.	5	1	5
4	Hydraulic Pressure on the lining / water infiltration in the masonry (south end)	Rapid dewatering of flooded southern tunnel section.	5	5	25	Drawdown of the water within the tunnel will result in increased hydrostatic pressures on the tunnel lining. Increased loading on the tunnel will result in overstressing. Increased stresses are a driver for lining collapses.	A dewatering system to be developed for the southern end of the tunnel in order to minimise hydraulic pressure on the lining. The pumping system needs to be maintained and operated on a continual basis.	5	1	5

Project Risk Assessment

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Risk No	Hazard/Risk Description	Cause	Before Mitigation			Consequence	Mitigation/Control Measures/Opportunity/Persons Responsible Client (CL), Designer (D), Contractor (CO)	Post Mitigation		
			Impact	Prob	Risk			Impact	Prob	Risk
Queensbury Tunnel: Generic and specific Hazards/Risks on the Tunnel & Shafts										
5	Surrounding rock fracturing	Drill & blast construction method.	5	4	20	The fracturing of the surrounding rock results in an increase of the stresses imposed on the tunnel lining.	Grouting of rock mass behind lining may be beneficial in areas with significant fracturing. The grout would fill the fractures and stabilise the rock mass. Additional investigative works required to include: - Ground probing radar (GPR) survey to verify voids behind the lining and separation of brick leaves - Intrusive cores through the tunnel lining and into the surrounding geology to confirm lining and ground parameters and rock quality. Undertake structural assessment of lining. Install ground improvement measures as required. Install remedial strengthening measures as required.	5	2	10
6	Water influx on the tunnel	Drill & blast construction method.	5	4	20	Fracturing of the surrounding rock mass will, where water is present, create a flow path for water passing through the ground. Fracturing will resulting in an increased amount of water ingress at the tunnel (and shaft) lining. Increased water ingress results in higher rates of deterioration including mortar wash out.	Pressure pointing of masonry and blockwork. Installation of controlled water paths through the coring/drilling of weep holes through the lining. Grout to be injected from within the tunnel in those areas where water ingress is excessive. Grout will fill in any cavities around the lining rock mass reducing water inflow.	5	2	10
7	Shaft Collapse	High levels of moisture ingress in the shafts results in lining weakening / deterioration. Lack of firm supporting strata at the top of the shaft linings. Lack of systematic maintenance. Failure of the tunnel lining below.	5	4	20	The major water inflows at all shafts have contributed to the deterioration of their linings and a number of failures in some sections, a further major collapse may occur. Rock surrounding the shafts may collapse (if not competent) following a shaft lining collapse. Following a shaft and/or surrounding rock collapse, a serious injury or even death of a member of the public may occur. 3rd party claims could also result. Settlement at the ground surface.	Additional investigative works required to include: - Point cloud survey - Ground probing radar (GPR) survey to verify voids behind the lining and separation of brick leaves - Intrusive cores through the tunnel lining and into the surrounding geology to confirm lining and ground parameters - Visual and tactile survey Undertake structural assessment of shaft linings & shaft heads. Install remedial strengthening measures as required. A monitoring strategy to be developed and operated during the decision making process (abandonment or reinstatement of shafts).	5	2	10
8	Possible effects on dwellings	Unknown condition of Shafts 5 & 6 and unknown capping of Shaft 6. Shafts 5 & 6 were not advanced to full depth. Lack of inspection data.	4	4	16	Adjacent properties might be affected by deterioration of the upper lining in Shaft 6. Condition of masonry capping slab in Shaft 5 is also unknown.	An inspection to take place in Shafts 5 & 6 to evaluate their current state. A capping slab to be considered for Shaft 6 if not existing.	4	2	8
9	Possible effects on dwellings	Water inflows in shafts cause failures in sections and lining deterioration; settlement at ground surface.	5	3	15	Adjacent property foundations could be compromised, leading to a potential injury or even death of a member of the public. 3rd party claims would probably result.	The shafts have been capped with reinforced concrete slabs (except Shafts 5 & 6). A structural assessment of these slabs should be undertaken (i.e. extraction of cores and laboratory testing) to assess the risk to the surrounding dwellings in the event of a shaft failure.	5	2	10
10	Presence of European Protected Species (EPS)	Delay to remedial works/construction	3	3	9	The tunnel and shafts may have high bat roost potential. If an existing roost is discovered it would either need to be maintained or an alternative roost created. This could potentially affect construction sequence and timeframe. Bats were not observed during the examination in July/August 2018.	Abandonment works would need to be carried out outside of the hibernation season, and in the event that a maternity roost is discovered, construction works would need to be carried out outside of the maternity season. Carry out Ecological survey early in project and schedule construction works accordingly.	3	1	3

Project Risk Assessment

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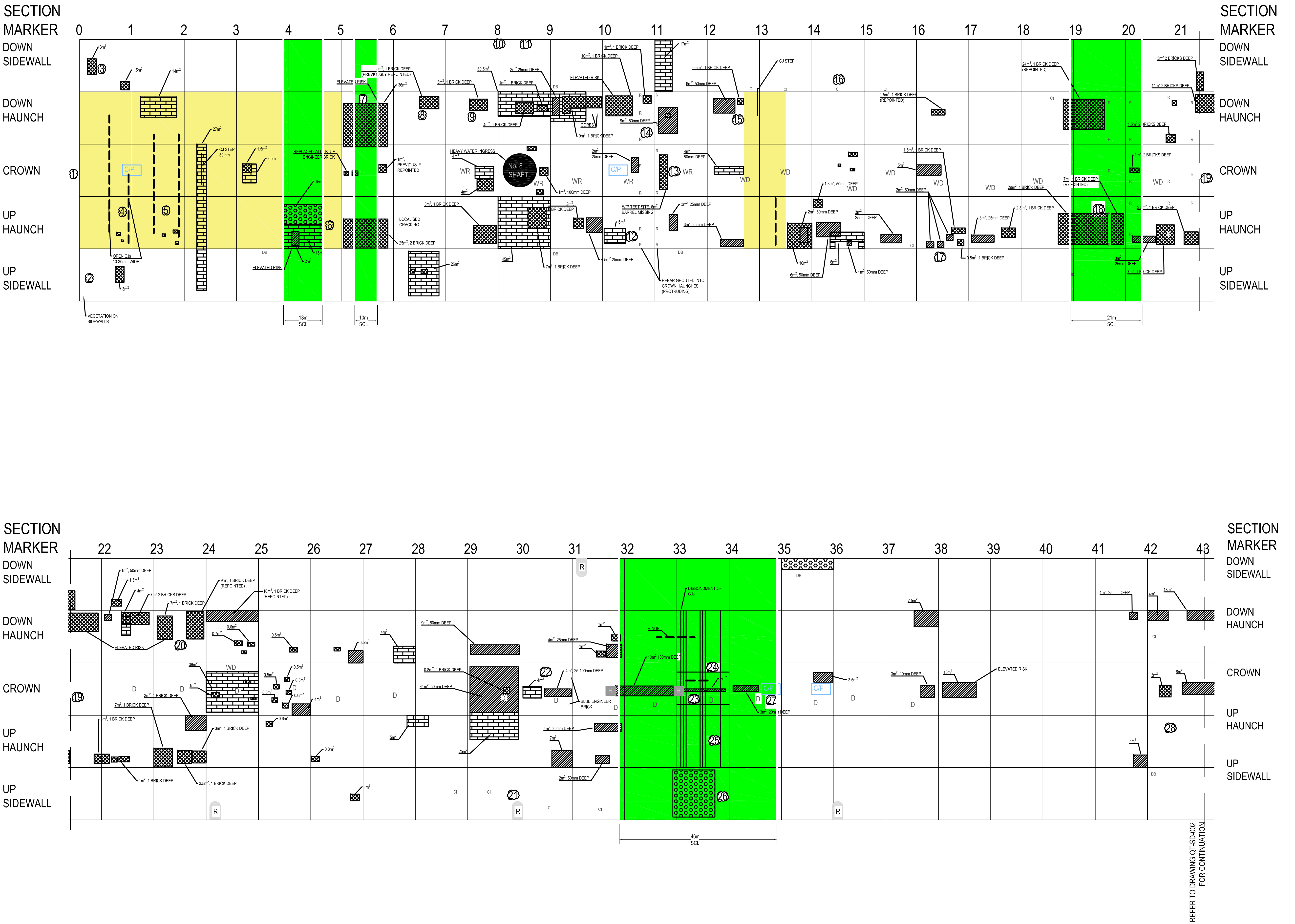
Risk No	Hazard/Risk Description	Cause	Before Mitigation			Consequence	Mitigation/Control Measures/Opportunity/Persons Responsible Client (CL), Designer (D), Contractor (CO)	Post Mitigation		
			Impact	Prob	Risk			Impact	Prob	Risk
Queensbury Tunnel: Generic and specific Hazards/Risks on the Tunnel & Shafts										
11	Hazardous materials: Asbestos	Historic tunnel abandonment and infilling of strines cutting is likely to have resulted in the dumping of prohibited waste. Subsequent flooding of the tunnel has caused waste materials to migrate into the tunnel.	5	5	25	Hazard to operatives entering the tunnel. Potential delays to construction / remediation works.	Undertake material hazard assessment within the tunnel. Remove and remediate if required.	5	1	5
12	Dangerous / confined working conditions during construction / remediation works.	Poor portal, tunnel and shaft lining condition. Remedial works on tunnel, shafts and portals.	5	5	25	Dangerous working conditions could result in injuries to, or even death of operatives.	Additional investigative works to include: - Point cloud survey through exclusion zone and at shafts - Ground probing radar (GPR) survey to verify voids behind the lining and separation of brick leaves/stonework - Intrusive cores through the tunnel lining and into the surrounding geology to confirm lining and ground parameters Remedial works to be designed in advance including: - Pressure pointing - SCL patch repair - SCL full sfrc lining - ARMCO culvert and backfill - Ground improvement - Drainage Remedial works construction sequencing to be designed in order to afford safety of operatives and third parties. All temporary and permanent works to be completed in compliance with CDM.	5	2	10
13	Inundation during remedial works	Water ingress and flooding at the southern tunnel portal	5	4	20	Programme delays, further costs and an injury or even death of an operative could occur.	A dewatering system to be designed and maintained at all times during the remedial works by the Contractor.	5	1	5
14	Future tunnel and degradation	Water ingress into the tunnel and shafts	5	4	20	The structural integrity of the tunnel could be compromised. Injury or death of a member of the public could occur. Possible 3rd party claims if tunnel and shafts are not adequately maintained.	A programme of regular inspections and maintenance will be required to ensure that the structures remain in acceptable condition. Ongoing funding will be required for inspections, monitoring and maintenance.	5	1	5
15	Difficulty evacuating site operatives and/or public users (post-remedial works)	Accident in the tunnel	5	3	15	An accident may cause injuries or death of an operative and/or a member of the public.	An emergency response plan needs to be in place during the remedial works and when the Tunnel is back in operation.	5	1	5
16	No access to south portal	Unable to obtain permission from land owner	5	3	15	It would not be possible to manage works from the southern end which would complicate the construction process and increase the safety risk to operatives.	Client and Contractor to engage in timely negotiations with land owner to facilitate access.	5	1	5

Appendix D - Indicative SCL Lining Locations



SAFETY, HEALTH AND ENVIRONMENTAL INFORMATION BOX

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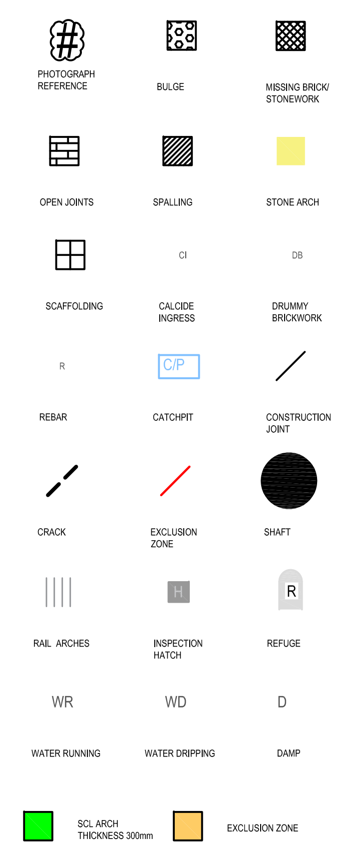
7. LOCATIONS OF DEFECTS ARE SHOWN INDICATIVELY.
8. REFER TO REPORT 60582061-REP002 (TUNNEL VISUAL CONDITION INSPECTION RECORD) FOR PHOTOGRAPHS.

KEY:



Creating Drawing	HH/JL AC	30/10/2018	P01
Revision Details	By Check	Date	Suffix

Purpose of issue

SCL REPAIR SCHEDULE

Client

City of Bradford Metropolitan District Council

Project Title

Queensbury Tunnel

Drawing Title

SCL REPAIR SCHEDULE

Northern Section SM0 - SM43

Designed	Drawn	Checked	Approved	Date
HH	HH/JL	AC	MWR	30/10/2018

AECOM Internal Project No.	Suitability	Project Manager
60582061		
Scale @ A1: Not to Scale	Zone/ELR/Mileage	

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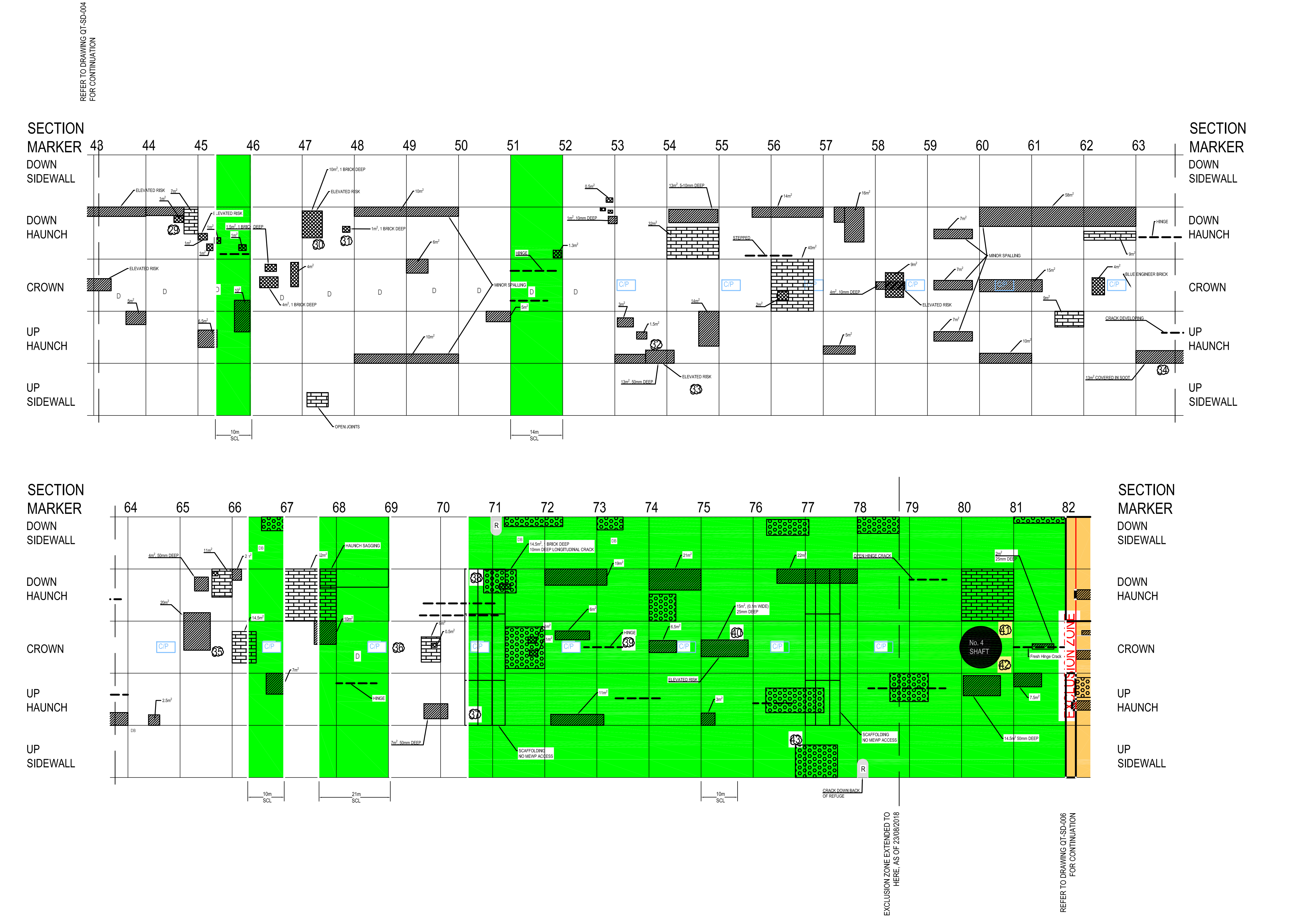
File Name: QUEENSBURY SCL REV2



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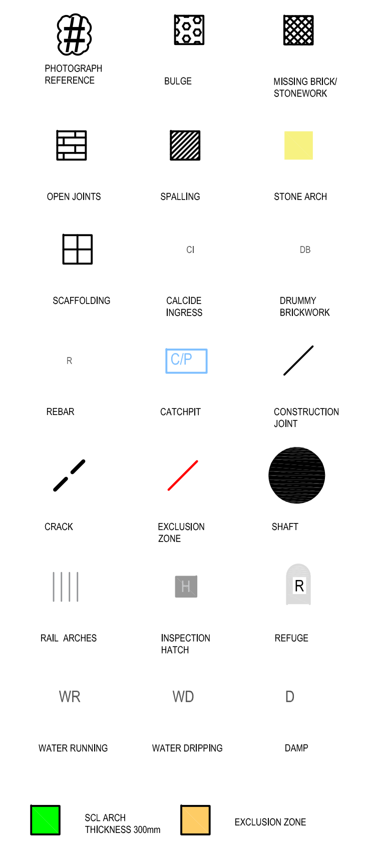

Creating Drawing	HH/JL AC	30/10/2018	P01
Revision Details	By Check	Date	Suffix

Purpose of issue

SCL REPAIR SCHEDULE

Client

City of Bradford Metropolitan District Council

Project Title

Queensbury Tunnel

Drawing Title

Schedule of Existing Defects Northern Sections SM43 - SM82

Designed	Drawn	Checked	Approved	Date
HH	HH/JL	AC	MWR	30/10/2018

AECOM Internal Project No.	Suitability	Project Manager
60582061		
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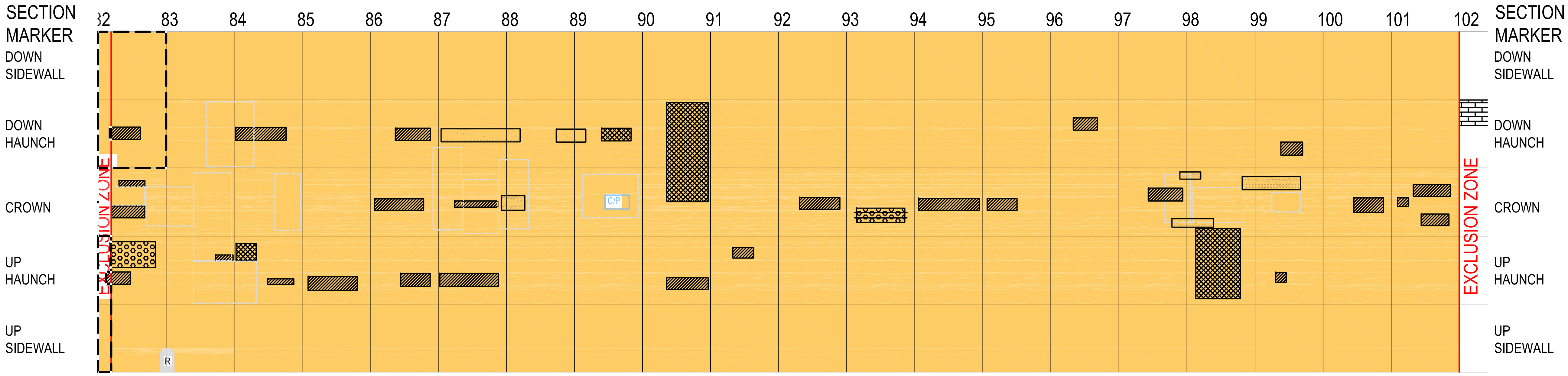
Rev: P01



EXCLUSION ZONE EXCLUDED FROM THIS ASSESSMENT
DEFECTS SHOWN BASED ON QTS TUNNEL CONDITION REPORT

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KEY:

- PHOTOGRAPH REFERENCE
- BULGE
- MISSING BRICK/ STONEWORK
- OPEN JOINTS
- SPALLING
- STONE ARCH
- SCAFFOLDING
- CI — CALCIDE INGRESS
- DB — DRUMMY BRICKWORK
- R — REBAR
- C/P — CATCHPIT
- CONSTRUCTION JOINT
- CRACK
- EXCLUSION ZONE
- SHAFT
- RAIL ARCHES
- H — INSPECTION HATCH
- R — REFUGE
- WR — WATER RUNNING
- WD — WATER DRIPPING
- D — DAMP
- SCL ARCH THICKNESS 300mm
- EXCLUSION ZONE

Revision Details	By / Check	Date	Suffix
Creating Drawing	HH/JL / AC	30/10/2018	P01

Purpose of issue

SCL REPAIR SCHEDULE

Client

Bradford City Council

Project Title

Queensbury Tunnel

Drawing Title

Schedule of Existing Defects Northern Section SM82 - SM102

Designed	Drawn	Checked	Approved	Date
HH	HH/JL	AC	MWR	30/10/2018

AECOM Internal Project No.	Suitability	Project Manager
60582061		
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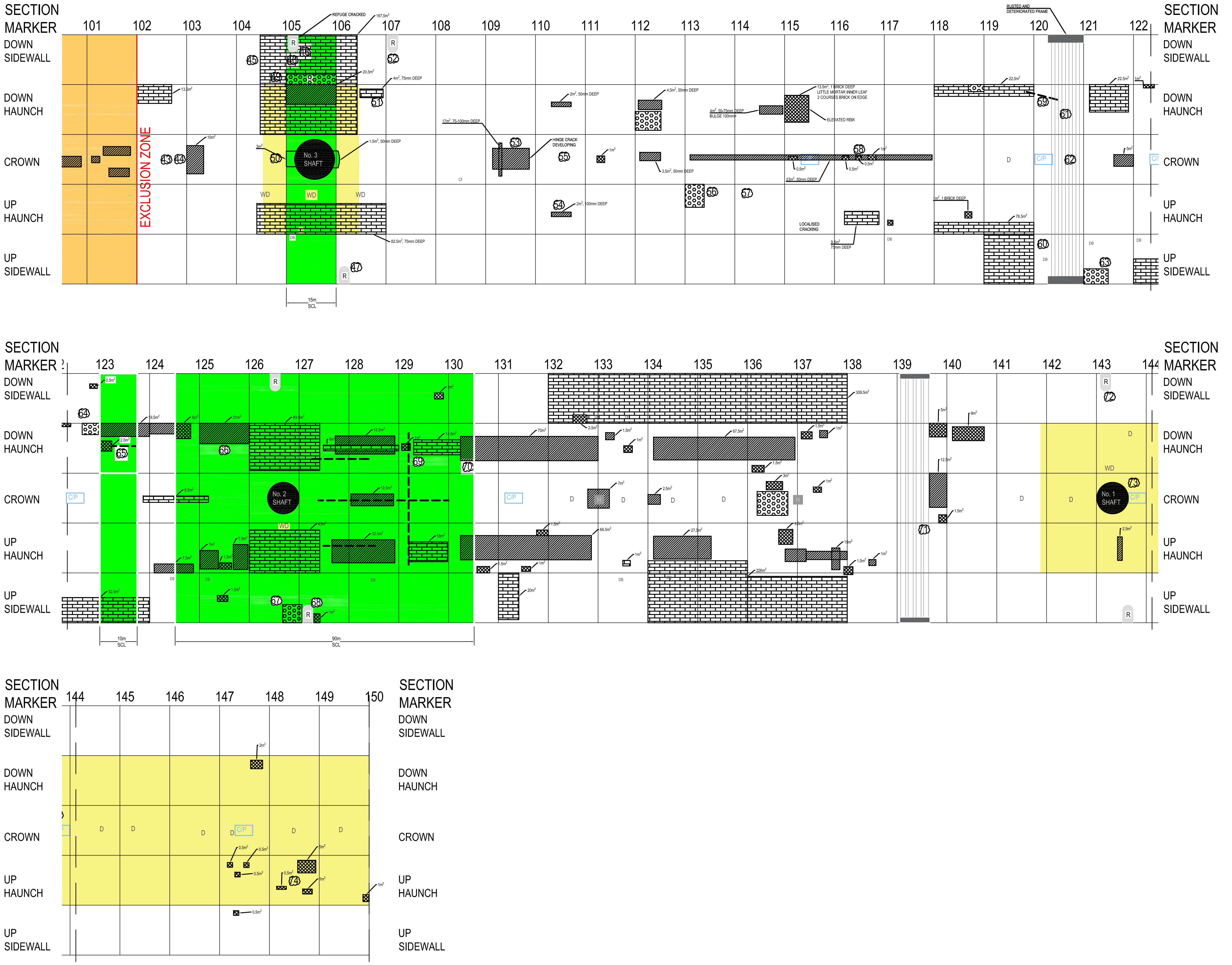

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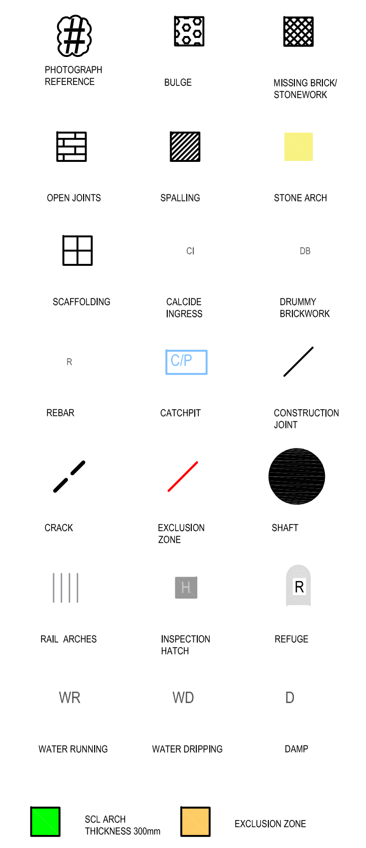

Revision Details	By / Check	Date	Suffix
Creating Drawing	HH/JL / AC	30/10/2018	P01

Purpose of issue

SCL REPAIR SCHEDULE

Client

City of Bradford Metropolitan District Council

Project Title

Queensbury Tunnel

Drawing Title

Schedule of Existing Defects Southern Section SM102 - SM150

Designed	Drawn	Checked	Approved	Date
HH	CN/JL	AC	MWR	30/10/2018

AECOM Internal Project No.	Suitability	Project Manager
60582061		
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