
**VOLUME 3 HIGHWAY STRUCTURES:
INSPECTION AND
MAINTENANCE**

SECTION 3 REPAIR

PART 4

BA 87/04

**MANAGEMENT OF CORRUGATED
STEEL BURIED STRUCTURES**

SUMMARY

Correction No. 1 (February 2006): page D/4, para D24, third formula for the live load from 8 wheels on one bogie load assessment. 0.32 in the denominator was corrected to 3.32.

Correction No. 2 (November 2009): page D/6, para D29, the definition of a_r was corrected from 3909 mm²/m to 3.909 mm²/mm.

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THE DEPARTMENT FOR REGIONAL DEVELOPMENT
NORTHERN IRELAND

Management of Corrugated Steel Buried Structures

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Contents

Chapter

1. Introduction
2. Durability
3. Inspection
4. Maintenance
5. Indicators for Priority of Repair Works
6. References and Bibliography
7. Enquiries

Appendix A CSBS in the UK

Appendix B Types of Inspection

Appendix C Examples of Summary Report Forms
and Sketches for Recording Data

Appendix D Guidance on Structural Assessment of
CSBS

Appendix E Deterioration of In-service CSBS

1. INTRODUCTION

GENERAL

1.1 A large number of corrugated steel buried structures (CSBS) have been installed over the past 40 years or so to act as culverts and underpasses below carriageways on the UK highway network. The span of most CSBS on the network is less than 4m. However, it is not uncommon to find larger-span structures and, although exceptional, structures with spans of up to 12m have been installed. From a structural point of view, the performance of most of the stock of structures has been excellent. The few exceptions have suffered excessive deformation generated either by poor construction practice or by ground movements due to differential settlement caused by mining works. However, CSBS require systematic management to ensure that they will achieve their 120-year design life.

1.2 CSBS, used as culverts, deteriorate mainly through hydraulic wear in the invert and along the wet/dry line. This removes protective coatings and exposes the steel substrate to corrosion. Deterioration of culverts and underpasses is also promoted through exposure to water laden with de-icing salts or sulfur compounds present in the backfill and surrounding soil. Deterioration is often localised and in the extreme results in perforation of the steel shell, which might lead to strengthening works or, if in an advanced state, replacement of the structure. However, no CSBS on the UK trunk road and motorway network has collapsed in service or suffered significant change in profile as a result of material deterioration. This might be due to:

- (i) the use of secondary protective coatings and sacrificial thickness of galvanising and steel; and
- (ii) the reserve of strength inherent in structures designed to BD 12: *Design of corrugated steel buried structures with spans greater than 0.9 metres and up to 8 metres*, (DMRB 2.2.6).¹

An important contribution to this satisfactory state of affairs has been made by proper inspections and ensuring that strengthening or replacement works are completed before the onset of weakening of the steel shell. Inspection and maintenance works will have an increasing role in ensuring that ageing CSBS remain in service.

1.3 Over the past twenty-five years a number of surveys have been carried out on the stock of CSBS on the trunk road and motorway network in the UK. It is apparent from these surveys that there were common forms of deterioration and their main causes were easily identifiable. Many CSBS are in good overall condition but have localised areas of deterioration. The most common forms of deterioration are internal corrosion at bolt holes and seams where water draining from the backfill enters the structure; failure of coatings and subsequent corrosion along the wet/dry line; and erosion of the invert by debris. For CSBS in the UK, severe corrosion due to chemically aggressive backfill is uncommon. The maintenance techniques include the application and/or refurbishment of protective coatings; the installation and/or refurbishment of concrete invert paving and, in cases of severe deterioration, the installation of structural liners.

1.4 There are a number of potential structural failure modes for CSBS, other than those due to the effects of corrosion, but, because of good construction practice, such modes are rarely seen in the UK. They include; the washout of the backfill; distortion of the steel shell caused by poor erection and backfilling practice; and plate buckling, or tearing of bolt holes or plate separation due to excessive ground movements. Such problems are likely to become apparent during or shortly after construction. For example, some early pipe arch structures built under embankments constructed on soft ground experienced buckling failure of the invert - these were repaired by the installation of structural reinforced concrete paving and have since performed satisfactorily.

¹ Hereafter referenced simply as BD 12.

1.5 The results of site surveys and other background research showed that timely preventative maintenance is the most economical means of extending the service life of a structure. The maintenance procedures and refurbishment techniques described herein are relatively straightforward to apply. The similarity in the structural types of CSBS and the common forms and causes of deterioration mean that the procedures and techniques described here are applicable to most CSBS.

1.6 It should be appreciated that the consequences of failure, particularly replacement cost and loss of service of an overlying carriageway, increase with the span of a structure.

1.7 To aid the inspection and maintenance process there are following appendices to this Advice Note:

- (i) Appendix A - information for identifying and determining the as-built physical properties of the common types of CSBS installed in the UK;
- (ii) Appendix B - details of the categories of inspection relevant to CSBS;
- (iii) Appendix C - summary report form suitable for recording inspection data;
- (iv) Appendix D - requirements for structural assessment, including the determination of suitable partial factors and the use of BD 12 for assessment; and
- (v) Appendix E - information on typical forms of deterioration seen in the CSBS in the UK, and on suitable methods of refurbishment.

1.8 The maintenance measures described herein are not to be regarded as prescriptive and should not preclude the use of other materials or systems proposed by engineers, contractors, or product manufacturers specialising in corrosion protection or the refurbishment of steel structures.

PURPOSE

1.9 The objective of this document is to provide guidance on the inspection, assessment and maintenance of CSBS.

1.10 Proper inspection and assessment are necessary to identify, plan and undertake appropriate maintenance work and thereby avoid the premature replacement of structures.

SCOPE

1.11 This document is applicable to CSBS having a span of 0.9m or more. Some sections of it might also be applied to smaller structures, particularly culverts, with the agreement of the Maintaining Agent (MA) and the Overseeing Organisation. Reference should also be made to BD 63 "Inspection of Highway Structures" (DMRB 3.1.4).

REQUIREMENTS

1.12 With CSBS it is necessary to consider:

- (i) material condition, i.e. thickness and soundness of protective coatings and invert pavings, the effects of corrosion and the residual thickness of steel;
- (ii) structural condition, i.e. alignment, cross-sectional shape, and the integrity of joints and seams;
- (iii) the general condition of ancillary structures such as head walls, parapets and adjacent earthworks; and
- (iv) aggressivity of the environment (backfill properties, groundwater, water in culvert, air quality etc).

OTHER RELATED DOCUMENTS

1.13 The design and construction of CSBS with spans greater than 0.9 metres and up to 8m in span are covered by BD 12. The requirements for providing and updating as-built records, maintenance manuals, operating manuals etc. are set out in BD 62 (DMRB 3.2.1).

1.14 The requirements for inspecting highway structures, other than road tunnels, are set out in BD 63 (DMRB 3.1.4) and details for reporting the results of inspections are provided in the accompanying Advice Note, BA 63 (DMRB 3.1.5). Specific inspection requirements and procedures of the Overseeing Organisations of England, Scotland, Wales and Northern Ireland are given in Appendices A to D respectively of BD 63 and BA 63. Advice on assessment by calculation for buried structures is given in BA 55 (DMRB 3.4.9).

1.15 Parts of the Specification for Highway Works (MCHW 1), its accompanying Notes for Guidance (MCHW 2) and the Design Manual for Roads and Bridges (DMRB) of particular relevance are:

- (i) the 5000 series of Clauses of the Specification and Notes for Guidance, maintenance painting of steelwork, which covers the protection of steelwork against corrosion;
- (ii) Clause 2501 which states the requirements for elements of a CSBS such as adjacent earthworks, structural components (including tolerances), galvanising, invert pavings, and protective coatings; and
- (iii) BD 87 (DMRB 3.2.2) Maintenance painting of steelwork.

2. DURABILITY

2.1 The durability of a CSBS is affected by site dependent factors such as its location and the properties of the surrounding backfill. It is also affected by the corrosion protection system, the size of the structure, its function and, for a culvert, the corrosivity of the water and its rate of flow through it.

2.2 BD 12 sets out the durability requirements for new installations, and these might be adopted as a basis for estimating the residual life of an in-service structure. Some information, such as the soil characteristics, might be available from construction records but other information, like the chemical constituents and flow characteristics of the stream water, might have to be determined from observations and measurements in the field. The category of aggressivity into which the site falls determines the likely rate of deterioration and this, along with observations of the current condition of the structure, indicate what (if any) additional protection measures are needed.

AGENTS OF DETERIORATION

2.3 There are a number of causes of deterioration to CSBS; some are specific to culverts but others affect both culverts and underpasses. For example, culverts deteriorate mainly through hydraulic wear in the invert and through cycles of wetting and drying along the wet/dry line. These remove the protective coatings and expose the steel substrate to corrosion. Deterioration may also be promoted in culverts and underpasses by contact with water containing chloride and/or sulfate ions. In such cases deterioration is often localised and, if severe, may result in perforation of the steel plates. Thus the durability of a CSBS will be critically dependent upon the performance of its protective coatings and invert paving. The factors currently taken into account in design (to BD 12) include the following.

Flow characteristics of the stream. Culverts may carry a continual flow of water, contain near stagnant water, or carry intermittent flows while the structure serves as a balancing pond or a flood relief channel. The flow of water and water-borne debris generate erosive forces that may lead to scour of the interior surface of the structure. Design requires information on the level of the mean winter flow and the likely maximum rate of flow.

Gradient of the stream. The flow velocity generated by the gradient and the presence or otherwise of a trash screen determines the size of particles carried through a culvert. Thus the gradient of the watercourse largely determines whether protection systems against erosion are needed.

Chemical composition of the water flowing through a culvert, and groundwater. Information is required in this connection, on pH and the concentrations of chloride and sulfate ions. The source of these ions include de-icing salts, agricultural chemicals (nitrates), and leachates from the soil.

Soil and backfill type. The aggressivity of the backfill and natural soil may have a detrimental effect on the durability of a CSBS. Factors to be assessed include pH, chemical constituents (chlorides, sulfates and sulfides), organic content, particle size, resistivity, uniformity coefficient, and liquid and plastic limits of the fines.

Atmospheric conditions. Air borne pollution generated by, for example, power stations and industrial process plants, might lead to the deterioration of exposed surfaces. CSBS sited close to the sea might be exposed to wind blown salt spray. Information on the aggressivity of the atmosphere can be gauged by reference to the map of relative values of acid deposition in the UK between 1986-1991 produced by the Agricultural Development and Advisory Service (ADAS, 1992).

MEANS OF ENSURING DURABILITY

2.4 There are a number of measures for enhancing the durability of CSBS. Most can only be put in place before or during construction, but others may be applied during the refurbishment of in-service structures.

Sacrificial steel The use of steel plates of sufficient thickness such that corrosion over the life of the structure does not reduce their thickness to less than that needed for structural adequacy.

Galvanising The primary protection system for all CSBS is a hot-dip coating of zinc, between 40 and 80µm thick. Galvanising protects the steel substrate by one or more of the following mechanisms; forming an

impervious barrier to oxygen; corroding in preference to steel (galvanic action); or forming an inert layer on its surface which reduces exposure of the zinc to further deterioration. Zinc corrosion products, such as oxides, hydroxides and basic carbonates, form a protective film on a zinc surface. Such films reduce the corrosion rate of the zinc to low levels, but they may be removed rapidly by chlorides, nitrates, and acids (such as sulphuric acid formed by the oxidation of sulfur compounds in the soil). Galvanising must be carried out after the plates have been rolled and corrugated and the bolt holes formed.

Secondary protective coatings These reduce exposure of the galvanising and steel to various agents of deterioration. Most are impervious to water and some provide excellent abrasion resistance. Some of the softer and thickly applied coatings, such as hot-dip bitumen, may seal seams and bolt holes and so limit the amount of water seeping into a structure. Over the past 40 years or so, the most commonly used secondary protective coating has been bitumen to the AASHTO M190 Standard; this requires the hot-dip coating to have a minimum thickness of 1.3mm. Other secondary protective coating systems have been used mainly for bolted segmental structures. These include cold-applied coatings (applied either by brush or spray) such as coal tar enamel in the 1960s and, more recently, Intex by ASSET International Ltd and Monoguard by Tubosider UK Ltd.

Invert protection. This includes the provision of pavings, drop inlets, and trash screens to protect the invert of the culvert from hydraulic wear by water and water-borne debris. (Clearly a paving will also protect the underlying coatings and steel shell.) For prefabricated pipes, the only works-applied invert paving is hot-dip bitumen to the AASHTO M190 Standard. Most of the invert pavings in bolted segmental structures are formed from reinforced concrete.

Carriageway drains. These may be sealed where they pass over a structure to prevent water, which might be contaminated with de-icing salts percolating down from the carriageway to the CSBS.

Membranes. These may be laid into the fill above the structure in a shape to encourage the flow of water, percolating down through the overlying carriageway and backfill, away from the structure.

Joint seals for bolted segmental CSBS. These prevent or reduce the seepage of water from the backfill into the structure through seams and bolt holes.

Impact protection. Barriers, height restrictions or rubbing boards might be installed to prevent damage by debris passing through a CSBS.

Repair of damaged areas. Following delivery to site and assembly.

COATING AND PAVING SYSTEMS

Prefabricated Pipes

2.5 About 85% of the in-service prefabricated pipes in the UK are provided with a secondary protective coat of hot-dip bitumen to the AASHTO M190 Standard. The remaining 15% have a plain galvanised finish or a cold-applied coating. Similarly, about 80% of the prefabricated pipes are provided with a hot-dip bitumen paving to the AASHTO M190 Standard. Only a few prefabricated pipes have concrete pavings.

2.6 A few older prefabricated pipes, 1.8m or less in diameter, were made from asbestos-bonded galvanised steel sheets. These sheets were manufactured by rolling asbestos pads into the molten zinc during the galvanising process. This provides a durable inert layer and gives an excellent bonding surface for bituminous coating and paving. Asbestos-bonded structures are only likely to be found in culverts placed in areas with particularly aggressive service conditions, such as the Trans-Pennine section of the M62.

Bolted Segmental Structures

2.7 In the UK, about half of the in-service bolted segmental structures are provided with a secondary protective coating of hot-dip bitumen to the AASHTO M190 Standard. About a quarter of the structures were constructed with a cold-applied coating. The remaining quarter were constructed with a plain galvanised finish, but some have subsequently been coated with bitumen epoxy paint during refurbishment.

2.8 BD 12/88 required all bolted segmental structures acting as culverts to be provided with a reinforced concrete invert paving. However, only about 30% of the total stock of bolted segmental structures on the UK highway network have been constructed since the release of this version of the Standard. Some earlier structures, which were likely to carry high peak flows, were also provided with a concrete paving, and in a number of others a concrete paving had been installed as a refurbishment/maintenance measure to combat deterioration at the invert. However, some invert pavings were not profiled to the shape of invert and so cause a restriction to the flow.

2.9 In bolted segmental structures, where an invert paving was not provided, an invert composed of settled sediments and rolled aggregates gets built up. Rock filled gabion mattresses have been placed in a few structures of this type as a protection measure.

3. INSPECTION

PURPOSE

3.1 An inspection is required to confirm material and structural integrity. It should provide information on both the severity and extent of any change in the structure as originally installed, or last inspected, both from a structural and material standpoint. The condition of ancillary structures e.g. headwalls, wing walls etc. should also be considered where they might affect the function of a CSBS. The results of an inspection might be used to complete a structural assessment and to specify the type and timing of further inspections or maintenance/refurbishment/upgrading works to a structure.

TYPES OF INSPECTION

3.2 The requirements for inspecting highway structures, other than road tunnels, are set out in BD 63 (DMRB 3.1.4). These documents set out the requirements for Acceptance and Maintenance Inspections. There are four categories of Maintenance Inspection:

- Superficial
- General
- Principal
- Special

and additionally an inspection for structural assessment.

An overview of these is given in Appendix B.

REPORTING

3.3 The procedures and requirements for reporting vary according to the type of inspection and, to some extent, on the findings of the inspection. They may also vary according to the requirements of the relevant Overseeing Organisation.

3.4 The results of an inspection should not be viewed in isolation. The change in condition with time must be established to define future inspection and assessment requirements, and to allow maintenance works to be identified and prioritised in a systematic manner. For

Superficial and General Inspections a detailed written report is not required, and the Overseeing Organisation gives the report format for a Principal Inspection. The results of an inspection should be presented in a format that identifies the critical factors and facilitates ready comparison with earlier and subsequent reports. Good quality colour photographs should be included in a report to catalogue areas of substantial structural or material deterioration.

3.5 The location of problem areas should be identified diagrammatically as shown, for example, in Figure C1 in Appendix C. Table C1 of Appendix C provides a form suitable for recording the severity and extent of deterioration.

3.6 **Note: Appendix C is not applicable where SMIS is used.**

MATERIAL CONDITION

3.7 As yet there is no known example of a structure in the UK which has undergone substantial deformation as a result of deterioration in its material condition. However, a number have deteriorated to such an extent that strengthening was required and some have been replaced prematurely. The commonest type of structure needing remedial works is a culvert where the invert was subject to scour action but where an invert paving was not installed.

CAUSES OF DEFECTS

Hydraulic Traffic

3.8 The debris carried by fast flowing water will scour the length of a culvert. In unpaved culverts it might remove secondary protective coatings along the invert which, in turn, might lead to the removal of the galvanising below the water level followed by corrosion of the steel substrate. Corrosion appears initially on the crests of the corrugations and, once established, a structure can be perforated over a significant length. Substantial corrosion of the invert might lead to large inward movements and eventual collapse of a structure. The backfill might be washed out through corroded sections during flooding leading to inadequate support, large ground movements and, ultimately, collapse. Severe corrosion along the invert of a structure with a

paving is rare, but the following forms of deterioration might occur:

- (i) Damage to coatings above the invert paving, where the culvert size is insufficient to contain the flow. The misalignment of a culvert, with respect to the original water channel, might generate turbulence in the stream, particularly at the inlet, and lead to deposition of debris blocking the waterway leading to overtopping of the road. Overtopping might also be generated by differential settlement along the length of a structure.
- (ii) Bitumen pavings deteriorate at the ends of a pipe, particularly at bevelled ends, where exposure to direct sunlight causes the bitumen to crack. Water flow may then break up the invert paving making the structure vulnerable to corrosion.
- (iii) Invert paving of structures in hilly or mountainous areas may suffer deterioration through the impact of large stones carried by high velocity flows.

Wet/dry cycles

3.9 Fluctuating water levels generate wetting and drying cycles that might deteriorate coatings. This may be particularly noticeable in culverts carrying little or no flow - here coatings may be removed in a narrow band along the whole length of a culvert. Bitumen coatings to the AASHTO M190 Standard are susceptible to this form of deterioration.

Seepage

3.10 Leachates from the backfill may enter the structure through bolt holes and seams. A common source of aggressive ions is run-off or ground water contaminated with de-icing salts. This leads to deterioration around the points of entry, and deterioration may be severe in a structure that has not been provided with a secondary protective coating. Deterioration is normally found at the crown and springing of a structure, but it may also be found around the seating of an arch structure on its concrete foundation where the construction detail allows water to collect on the soil side.

3.11 Often the seepage of leachates into a structure shows up as the formation of white deposits around bolts and seams, but in some cases these might only be carbonate deposits. The seepage of corrosive leachate will lead to the loss of galvanising and corrosion of the

steel substrate. However, even where there is extensive deterioration of the interior, deterioration on the soil side of the structure might be negligible.

Backfill

3.12 The use of an aggressive backfill has led to extensive and severe deterioration of a handful of structures in the UK. It can promote severe pitting corrosion or a more even degradation to the steel on the soil side. Most at risk are structures that do not have a secondary protective coating on the soil side. The rate of deterioration is usually rapid and structures may be holed shortly after construction. BD 12 does not allow the use of highly aggressive backfills but on occasions they have been used in error. If the presence of non-water soluble sulfides in the backfill is not detected, in time it may form a highly acidic environment and, severe pitting corrosion. With less aggressive backfills, deterioration takes the form of more general corrosion on the soil side and internal damage at seepage points as described above.

3.13 There was less control over the quality of backfill used in the construction of CSBS before the release of BD 12 in 1982. In addition, rules governing the extent of good quality backfill around a CSBS were less onerous. However, most structures in the UK, including those predating 1982, have been provided with granular self-draining backfill and secondary protective coatings.

Chemical Composition of Water Flowing Through Culverts

3.14 The protective coatings to the invert of a culvert may be degraded through contact with water having a low or a high pH value, containing industrial or agricultural effluent, or de-icing salts. However, since the flow in most culverts is contained within the invert paving in dry weather, few structures have been identified where this has caused a problem, but there are cases where corrosive water has led to the deterioration of buried surfaces.

Atmosphere

3.15 There is little evidence of deterioration of the exposed surfaces of CSBS resulting from atmospheric pollution. Air borne deterioration is limited, by and large, to coastal regions where the exposed surfaces of a CSBS have not been provided with secondary protective coatings.

Stray Electric Currents

3.16 Stray electric currents may lead to rapid but localised deterioration. Currents may derive from leakage of damaged buried electrical cables, or earth currents from railway electrical power systems. There have, however, been no reported incidences in the UK of deterioration of CSBS due to stray currents.

INSPECTION RECORDS

3.17 At Principal and Special Inspections, to assess the material condition of a structure and to provide data for reference during future inspections, an inspector should make a note of the following:

- **secondary coatings (if any):**
 - general statement on condition, and thickness where sound;
 - locations of deterioration, and severity of deterioration;
- **galvanising:**
 - general statement on condition, and thickness where sound;
 - locations of deterioration, and severity of deterioration;
- **steel:**
 - general statement on condition, and at Special Inspections intact thickness (measured through galvanising);
 - condition around bolt holes and edges of seams;
 - locations of deterioration and minimum residual thickness; locations should be defined where the loss in thickness is greater than 10%. At Special Inspections, where the thickness of the steel has been substantially reduced but the loss is not evident on the exposed surface, cores should be taken to determine the condition of the buried face;

- **invert paving:**

- general descriptive statements, and an assessment of whether the opening is sufficient to contain winter and peak flows;
- details of condition along the structure, i.e. whether it is unworn, worn but still providing protection to the structure, or, worn and shell exposed.

MEASUREMENT AND TESTING

3.18 Measurements of the residual thickness of the steel plates and protective coatings are essential for judging the extent of deterioration and for assessing the residual structural capacity. These measurements would normally only be carried out routinely in Special Inspections. However, they could also be made during Principal or General Inspections to assess the need for a more detailed inspection, provided special measuring devices are available. Because of access problems, such measurements might only be taken at the ends of a small span structure. Appendix A provides information for identifying and determining the as-built physical properties of the common types of CSBS installed in the UK.

Secondary Coating

3.19 The thickness of a secondary coating can most easily be established using a non-destructive thickness meter. These devices normally provide a measurement of the distance between the face of the probe and the steel substrate. The reading will be the aggregate thickness of the galvanising and secondary coatings, but the thickness of zinc is usually small compared to the thickness of the other coatings and adjustments can be made readily. It is relatively easy to differentiate between the types of bitumen coating used. Hot-dip bitumen applied in accordance with the AASHTO M190 Standard is normally 1.3mm thick, whilst the current specification for cold-applied material requires a 700µm thickness. However, older bituminous and coal tar coatings have been applied in situ in 100 to 200µm thick layers.

Galvanising

3.20 The pre-galvanised steel strip used in the manufacture of helically wound corrugated pipe normally has a coating thickness of 43µm, whilst that for riveted and bolted structures (galvanised after fabrication) varies from 50 to 80µm depending on the

thickness of the steel. The cover meter used to measure the thickness of the secondary coatings may also be used to measure the thickness of the galvanising where it is exposed.

Steel

3.21 A measurement of the thickness of steel may be obtained using an ultrasonic thickness gauge. Such devices are easy to operate and can measure accurately the thickness of sound steel but, provided loose rust has been removed, measurements can be made through a corroded surface.

3.22 Core samples may be taken at Special Inspections when it is considered necessary to examine the condition of the coatings on the soil side. This usually requires the use of a small electric generator and drill. Where corrosion is promoted by the ingress of leachates, core samples could be taken 150mm above and below the points of major seepage. The requirement for core samples would normally be expected to form part of a Special Inspection.

Properties of Water and Backfill

3.23 In exceptional circumstances, where, for example, the cause of deterioration has not been identified, it might be necessary to determine the variation in the velocity, depth and chemical content of the water passing through a culvert. The results of tests on samples taken at infrequent intervals (of say more than one week) may not provide a detailed picture of events, particularly where flows are intermittent or where de-icing salts are spread on the overlying carriageway. In which case, sensors may have to be installed for a reasonably long period. It will be difficult to obtain representative samples of the backfill through small diameter core holes drilled through a structure and so it is usually necessary to take samples from test pits at the ends of a structure. It might also be necessary to obtain samples from boreholes along the line of a structure, but this might require a lane closure.

GUIDANCE ON ASSESSING STRUCTURAL CONDITION

Distortion

3.24 Substantial local deflection of the upper part of a structure is usually the result of the encroachment of construction plant, usually heavy earth moving equipment, during and immediately following backfilling. Encroachment may lead to overloading of the steel shell, but large deformations may not be

apparent until the structure is covered with backfill. Gross changes in cross-section may also result from either the backfill or the foundation failing to provide adequate support to the structure. Closed invert multi-radii structures are particularly susceptible to deformation deriving from inadequate foundation support. This is recognised by the design rules in BD 12 which limit the corner bearing pressures of such structures.

3.25 Due to their inherent flexibility, CSBS are often installed through embankments constructed on poor ground and, therefore, where significant longitudinal settlement could be anticipated. Such settlements are a function of the consolidation properties of the underlying subsoil, and it may be many years before the rate of settlement becomes negligible. Provided that a structure is surrounded with an envelope of good quality backfill, it should accommodate substantial settlements safely and without unacceptably large changes in cross-section. A concern with the excessive longitudinal settlement of culverts is the separation of circumferential seams or joints, thereby permitting water to pass into the surrounding backfill promoting washout, a lack of support and progressive deformation. The potential for the migration of fill should also be appreciated when inspecting the head walls and aprons of culverts.

3.26 Distortion of a structure might be induced by:

- (i) large ground movements, for example where:
 - (a) the depth or properties of the subsoil vary substantially;
 - (b) excavation has removed the lateral support to a structure; or
 - (c) mining works have been undertaken;
- (ii) poor construction practice, for example where:
 - (a) poor quality backfill has been used;
 - (b) compaction has been inadequate; or
 - (c) uneven loading occurred during compaction operations;
- (iii) uneven loading, for example where:
 - (a) there is a large difference (albeit temporary) in the level of the embankment on either side of the structure; or

- (b) the applied highway loads vary along a structure (for example where it runs parallel to a carriageway).

It is improbable that the above would be met with a CSBS designed and constructed in accordance with BD 12. The distortion of a CSBS should be relatively small and should not increase significantly in service: continuing movements are a sign of instability and must be investigated as a matter of urgency.

Inspection Guide

3.27 To assess the structural condition of a CSBS and to provide data for reference during future inspections an inspecting engineer should make a note on the following:

- (i) shape, alignment and condition of structure;
- (ii) longitudinal settlement - approximate deviation from mean gradient, and separation of any joints or seams;
- (iii) cross-section/profile:
 - the nominal vertical and horizontal dimensions;
 - the location of areas of significant deviation from the nominal dimensions, and whether deviation is outside established limits or constitutes a serious non-uniformity;
 - the existence of reverse curvature;
- (iv) the presence of voids within adjacent backfill - this might be identified through the build-up of fines within a structure, depressions in the overlying carriageway, by tapping the steel shell (to detect 'hollow areas') or by ground penetrating radar.

Measurements

3.28 In most cases it should be sufficient to measure the dimensions of a structure, i.e. span and height using a graduated telescopic pole or Invar steel wire/tape. But other devices, such as a laser distance meter, might also be used.

Ancillary Structures

3.29 Observations should be made on the condition of the following:

- aprons:
 - general assessment of soundness, and whether or not the apron prevents water flowing through the backfill along the outside of the structure;
- head walls:
 - general assessment of soundness, and whether or not the head wall prevents water flowing through the backfill along the outside of the structure;
- catch pits, drop inlets, trash screens, protective gates and the like:
 - general statement of condition and assessment of efficiency and requirement for cleaning;
- embankments:
 - identification of any signs of instability which could affect the performance of the structure;
- concrete relieving slabs:
 - identification of any signs of settlement under leading or trailing edges and potential for voids forming under the slabs;
- drainage systems of embankment and carriageway:
 - general statement of condition;
 - identification of any likely problem areas such as broken gullies in overlying carriageway;
- road surfacing:
 - general statement of condition;
 - identification of any problem areas such as settlement troughs and cracking adjacent to CSBS;
- parapets/handrails:
 - general statement of condition.

STRUCTURAL ASSESSMENT

3.30 The objective of a structural assessment is to obtain a realistic estimate of the stability of the in-service CSBS. It is important to determine the effect of any deterioration, such as localised corrosion, on structural capacity.

3.31 A visual structural assessment of a CSBS need not be verified by calculation unless there are signs of distress such as bulging or severe corrosion. However, such an assessment must be carried out to assess the load carrying capacity of a structure where one or more of the following apply:

- (i) The deviation of the cross-section of the structure from the nominal dimensions exceeds:
 - (a) closed invert, circular structures 5%;
 - (b) closed invert, multi-radii structures 3%;
 - (c) arch structures 3%.
- (ii) A structure exhibits signs of serious deterioration such as cracking around the boltholes, separation at seams, local buckling or signs of reverse curvature.
- (iii) The steel thickness over a substantial area or length of the structure has been reduced by more than 10% of its original value. (This does not apply to spot corrosion affecting say less than 1m length of a longitudinal seam or plate.)

Items (i) and (ii) would normally be recorded during a Principal Inspection whilst item (iii) would normally be recorded during a Special Inspection.

3.32 Checks on wall stress, seam strength and buckling should be carried out using the design equations and method set out in BD 12 This sets out the partial factors of safety to be applied in design. These factors take into account uncertainties in loads, design method, and material properties. However, many of these uncertainties are much reduced for an in-service structure that is within tolerance on shape and appears to be performing adequately. Thus in assessment it is unnecessary to apply all the values of the partial factors used in design. For example, as the depth of cover may be readily measured and the design live load is relatively onerous, nominal dead and live loads may be used in assessment checks. Appendix D gives guidance for carrying out a structural assessment and provides a worked example.

3.33 The seams in bolted structures are designed to fail in compression through distortion and tearing of the plates around the bolts, but not through failure of the bolts. Bolt failure is a potentially catastrophic failure mode because the failure of a single bolt could lead to load shedding and subsequent overloading of adjacent bolts, thus ultimately the failure of all the remaining bolts along a seam. However, given the factors of safety involved in the design of seams, bolt failure is improbable. According to BD 12, the design seam strength is to be determined from tests in which bolt failure must not occur. Nonetheless, where the bolts on a structure are badly corroded an assessment of residual strength must be carried out as a matter of urgency. This is, however, difficult to achieve and the best approach might be to take a core to recover a bolt and surrounding section of the plates that form the seam. This will allow a visual inspection and measurements to be made on the extent of corrosion. Where corrosion at a seam is severe, immediate strengthening will be required - where corrosion is localised, liner plates may be used to provide strengthening.

3.34 The assessment of a structure whose shape is outside the deviation limits for cross-section is not straightforward and may require specialised analysis. In general:

- (i) the greater the deviation from the nominal cross-section the greater the loss in capacity; and
- (ii) the larger the span the greater the sensitivity to deformation.

Where continuing movement of a structure is evident, the cause of the instability must be investigated and immediate steps taken to restore an adequate margin of safety.

3.35 The assessment of a structure that has suffered longitudinal distortion may also require specialised analysis. Such distortion might be caused by differential settlement or by mining subsidence. Hogging ground strains are particularly important as these reduce the area of section (**a**) and moment of inertia (**I**) of the corrugation. Appendix D provides further details of these effects.

3.36 Where a structure fails an assessment, guidance on how to proceed is provided by BA 79 (DMRB 3.4.18). Depending upon the type and extent of the deterioration, a structure may need immediate strengthening. However, the assessing engineer may re-assess the structure by carrying out tests to determine more reliable values for the properties of the soil or

other materials. The value of the constrained soil modulus (M^*) for the surrounding backfill may be obtained from in situ tests carried out in accordance with Chapter 5 of BD 12/01. The check on buckling may be made using this value rather than the minimum values provided in BD 12. The yield strength of the steel plates, which is used in the calculations, may be obtained from laboratory tests on samples taken from the structure. In this way a structure may pass its re-assessment.

4. MAINTENANCE

GENERAL

4.1 Given that regular and adequate inspections are undertaken, the most common form of maintenance will be the refurbishment of protective coatings and pavings. The need for structural strengthening due to excessive deformation should be a rare occurrence because in most cases deflection would have been evident as the structure was loaded during construction and appropriate action taken then. Nevertheless, it is possible that material deterioration could reduce the margin of safety below an acceptable limit and, therefore, options for structural strengthening are also considered in the following.

4.2 To ensure a long service life, secondary protective coatings and pavings must be maintained in good condition. It is preferable to prevent corrosion than to rely on the presence of sacrificial metal to provide stability. This is particularly true for culverts where erosive flow may lead to rapid deterioration. Not only does the cost of material refurbishment escalate where galvanising has been removed but, more importantly, providing an effective protective coating is more difficult to achieve where the steel shell is corroded. The maintenance of secondary coatings etc may be particularly important in older structures as those predating the introduction of BD 12 in 1982 are unlikely to have been provided with sacrificial steel thicknesses on their inaccessible surfaces.

4.3 In some situations it will be feasible and in the long term prove economic to undertake upgrading works additional to material refurbishment. For example, the durability of a CSBS acting as a culvert may be enhanced through the installation of an invert paving, if one is not already present, or by raising the sides of the existing paving to fully contain the flow.

4.4 In all cases the Health and Safety Executive (HSE) confined working space guidelines should be followed (HSE, 1997). See also the Confined Spaces Regulations 1997 (The Stationery Office, 1998). The relevant documents for Northern Ireland are HSENI Safe Work in Confined Spaces in Northern Ireland (ACOP) and Confined Spaces Regulations (NI) 1999.

PREVENTATIVE MAINTENANCE

4.5 This work might consist of one or more of the following:

- (i) placement of a concrete invert paving in unpaved structures, to BD 12, Chapter 13 standard;
- (ii) raising the sides of the existing paving;
- (iii) placement of coated, galvanised steel/GRP sheets along the wet/dry line;
- (iv) grouting the fill to minimise seepage (see 4.25);
- (v) construction of drop inlets /trash screens to remove solids; and
- (vi) provision of a secondary protective coating to the maintained surface of a plain galvanised structure.

Illustrations of some of these works on typical structures are given in Appendix E.

REFURBISHMENT

Surface Preparation

4.6 Effective refurbishment depends on the proper preparation of the galvanised steel surface prior to the application of secondary coatings. Where the zinc is intact it may be coated after cleaning, although the use of a primer and/or an adhesion promoter will be needed where secondary protective coating systems other than bitumen are used. Where zinc has been removed, either locally or overall, and the steel substrate has corroded, the corrosion products should be removed by abrasive blast cleaning. But, where corrosion is restricted to small discrete areas, mechanical cleaning by abrading may be more suitable.

4.7 The Series 5000 Clauses of the Specification for Highway Works (MCHW 1) sets out the requirements for the protection of steelwork against corrosion. These are provided for the maintenance painting of in-service steel structures. The Clauses provide requirements for cleaning steel and for the quality of surface preparation to be achieved before the application of protective coatings. Clause 5003 provides the rules governing

abrasive blast cleaning and mechanical abrasion, and Clause 5004 sets out the required workmanship standards for surface preparation by blast cleaning. For most refurbishment work, it should be satisfactory to adopt the preparation standard set out in Clause 5004.1.v.a 'Clean Steel' or b 'Sa2' quality or to Bright steel by grinding or to 'Sa3' quality. (Clearly preparation to a sound standard is essential if the refurbishment is to return the surface to a suitable condition ready for the application of secondary protective coating). Guidance on the visual assessment of surface cleanliness is given in ISO 8501-1 (1988) and ISO 8501-2 (1994). BD 87 provides general guidance on maintenance painting of steelwork.

4.8 Where surface preparation to Clause 5004.1.v 'Clean Steel' or 'Sa2' quality is unattainable or where additional preventive work is to be undertaken, for example, the installation of a reinforced concrete paving, such stringent surface preparation is not necessary. Then it will be satisfactory to ensure that the surfaces are free of detrimental contamination. Where it is not feasible, for practical or economic reasons, to prepare the surface to the standards referenced above, the surface should be abraded to remove all loose rust before applying a bitumen coating. Although not as effective as the more rigorous and expensive processes, in many cases this should postpone the need for more costly refurbishment work.

4.9 Surface preparation, including the removal of contaminants and residues are described in Clause 5002. BD 87 gives advice about carrying out a pre-specification overall survey and feasibility trials to determine the appropriate level of surface preparation.

Secondary Coatings

4.10 Selection of primer (usually epoxy- or zinc-based) and an associated top coat should be based on the manufacturer's recommendations with consideration given to the following:

- standard of surface preparation to be achieved;
- possible presence of moisture;
- choice of primer;
- choice of top coat;
- ambient temperature;
- required life of the coating.

BD 35 (DMRB 2.4.1) provides a quality assurance scheme for generic types of primer, paint and similar protective coatings which may be used on Overseeing Organisation schemes. Annex A of BD 35 contains Item Sheets for each generic type of coating and the information provided on these includes recommendations for use and the performance test requirements. A list of paint manufacturers whose formulations have Highways Agency registration is contained in SA 1 (MCHW 0.3.1)

4.11 In most cases the refurbishment of bituminous coatings involves the removal of all areas of loose/ brittle bitumen and the cleaning of the exposed galvanised surface. The use of primer coats to the new bitumen coating will not normally be necessary for a weathered zinc surface, but a bright zinc surface can be passivated with a mordant wash, such as 'T wash' (Item 155 in Annex A of BD 35). It will generally be impossible, and unnecessary, to achieve a 1.3mm thickness of bitumen - as originally provided to many structures, but the target finished thickness of cold-applied bitumen should exceed 200µm. A coating of thixotropic bitumen complying with Item 141 in Annex A of BD 35 may be suitable for refurbishing bituminous coatings.

4.12 For more extensive refurbishment, the application of secondary protective coatings other than bitumen-based products should be considered.

4.13 For culverts, following the application of a suitable moisture-tolerant primer (such as Item 110 in BD 35 - zinc phosphate epoxy blast primer), the use of coal tar epoxy-based products (Items 150 or 151 in BD 35) having a total thickness in excess of 200µm should provide effective protection. For underpasses it might be necessary, for aesthetic reasons, to consider the coating of the entire interior rather than just the area in need of refurbishment. The use of a zinc phosphate primer plus a high-build epoxy undercoat (Items 112 or 116) followed by a finishing coat of acrylic urethane (Items 168 and 169) would be appropriate. Alternatively, the use of a moisture-cured undercoat (Item 162) and a moisture-cured polyurethane finish (Item 164) may be suitable.

4.14 Manufacturers should be asked for their view on the most appropriate coatings for the given service condition. Specialised contractors who offer their own proprietary protective systems could also be approached. Consultation would be worthwhile where the deterioration of the structure is extensive. Proof of the compatibility of coatings and primers should be provided.

Refurbishment of Invert Pavings

4.15 The on-site refurbishment of a factory-applied bitumen paving, for example, as covered by the AASHTO M190 Standard, could be undertaken using a bitumen mix of similar specification - the mix being heated on site and trowelled into place. However, there is little experience in the UK of this technique. Its effectiveness is dependent upon the control exercised on the temperature of the heated repair material and the proper preparation of the surface, i.e. it must be clean and dry. Effective refurbishment might be difficult to achieve in practice and, because deterioration of this type of paving commonly occurs across its entire width, the use of mass concrete, coated steel sheets or glass reinforced plastic (GRP) profiled units may be simpler and more effective (see Appendix E).

4.16 The repair of in situ concrete pavings may be undertaken using conventional techniques. However, where serious deterioration has occurred, the installation of a new paving should be considered because this is likely to be the most effective solution in the longer term. The installation of drop inlets and the like should be considered for rapid water flows.

New Pavings

4.17 Where material deterioration has occurred below the horizontal axis of a structure, the installation of a concrete invert paving may provide an excellent means of rehabilitation and also greatly improve the protection of the steel shell. All corroded areas must be treated prior to placing a new paving. The specification given in BD 12, Chapter 13 for installing concrete invert paving should be followed. In smaller span structures where the conditions of abrasion and flow are not severe, and where it is not feasible to install a reinforced concrete paving, use of unreinforced concrete, hand trowelled into place, may be satisfactory. For more demanding service conditions a reinforced concrete paving or suitable alternative to the requirements of BD 12 will be required.

4.18 The hydraulic capacity of a culvert will need to be considered prior to placing an invert paving. However, a smooth invert will have better flow characteristics than a corrugated plate.

STRUCTURAL STRENGTHENING

4.19 In the event that the strengthening of a structure is deemed necessary one or more of the following options described below may be used. (Where

appropriate, for example, with the strengthening and relining solutions, the standard Technical Approvals procedures should be followed.) Some useful information on techniques for enhancing structural stability is provided by Abdel-Sayed et al (1993), the California Department of Transportation (CALTRANS, 1993) manual on culvert restoration techniques, the Federal Highways Authority culvert repair practices manual by Ballinger C A and Drake P G (1995), Alexander et al (1994), and SETRA (1992).

Structural Invert Paving

4.20 A reinforced concrete invert paving can be provided as a strengthening element where the upper portion of the structure is sound but where the invert has deteriorated to such an extent that it fails structural assessment. Rather than replacing or relining the entire structure it is possible to provide a reinforced concrete paving. Details of the extent, strength of concrete and the depth of cover to the reinforcement should be essentially as given in BD 12, Chapter 13. The shear connection between the shell of the CSBS and the paving must be sufficient to transfer the ring compression from the shell to the paving, and that must be sufficiently strong to carry the ring compression. The shear key between the paving and the structure may be provided through the use of suitable steel connectors either fixed through or welded to the plates. Alternatively, in bolted structures, it may be possible to provide a shear key by providing extensions to the bolts used to join the plates.

Relining

4.21 A structure may be strengthened through relining. Rigid liners may be used but, given that CSBS are designed as 'flexible' structures, it is more fitting to provide flexible liners. Depending upon the span and shape of the existing structure, these may take the form of a smaller diameter CSBS, or glass reinforced plastic sheets, and they may be shaped to match the existing profile. The liner may be pre-assembled external to the structure and dragged or slipped into the existing structure. The annular space between the structure and liner must then be grouted and care must be taken to avoid flotation of the liner during the grouting operation. Provision may be made for:

- (i) guide rails along which the liner can be dragged;
- (ii) spacers or adjuster bolts to ensure that the correct annular space is maintained between the liner and structure; and

- (iii) grout plugs around the periphery of the liner and at the crown at, say, 1 to 1.5m centres.

For larger structures an alternative to the use of liners would be to use sprayed concrete and steel mesh reinforcement.

4.22 A possible disadvantage of relining a culvert is the reduction in hydraulic efficiency resulting from the reduction in cross-sectional area. However, the installation of a relatively smooth liner into a CSBS may well improve its hydraulic efficiency. Guidance on calculating hydraulic efficiency may be obtained from the CIRIA publication by Ramsbottom et al (1998). In the design of many older structures the hydraulic requirements were expressed as a rectangular area whereas the CSBS provided a larger than required cross-sectional area because the designated rectangle was wholly contained within a standard profile. Thus CSBS often provided a much higher hydraulic capacity than required. It should also be appreciated that, irrespective of hydraulic requirements, the minimum diameter of culverts placed under motorways and trunk roads was of the order of 1.1m and so ample excess capacity often exists in structures of this size.

4.23 If strengthening is required because of corrosion of the buried surface, consideration should be given to the use of a waterproof grout and/or the application of a high quality protective coating system to the liner.

4.24 The cross-sectional area, shape and length of the structure to be lined will limit the choice of suitable materials, but other constraints include the existence of connections with other structures and with aprons, head walls etc. The materials and techniques described below could be considered.

- (i) **Spirally wound corrugated pipes.** The use of these for relining is limited to circular profiles of up to about 3m in diameter. Sections may be winched or jacked through the existing structure. To improve hydraulic efficiency the lining may be provided with a paving covering more than 25% of the periphery/circumference as commonly used.
- (ii) **Plastic pipes.** The use of plastic pipes is also limited to circular profiles of small to medium diameter. Such pipes have good hydraulic characteristics but they have limited strength and may be relatively expensive. Plastic pipes should not be used where they could be vandalised or set on fire.

- (iii) **GRP units.** These units, shaped to fit the profile of the structure, are easy to place and have excellent hydraulic characteristics but, like plastic pipes, have limited strength. Their wall thickness may, however, be varied to suit.
- (iv) **Bolted corrugated plates.** There are no limits to the size and shapes available for bolted plates but, since the product is designed to be assembled from the outside, it is likely to be suitable only where short lengths are to be relined. Arches are a possible exception to this as a lining may be jacked or winched along the bottom of the structure and then lifted into position by jacks.
- (v) **Steel liners.** These are designed for use in tunnels and provide the simplest and most suitable means of relining larger CSBS with limited areas of deterioration. The plates are flanged and of a size that may be handled manually and all bolting is done from the inside. They may be manufactured to fit any profile having a diameter or span greater than 1.2m.
- (vi) **Concrete liners.** Precast reinforced concrete sections may be used to reline larger diameter structures, particularly those with structural pavings. Sprayed concrete might also be applied to all or part of larger span structures, with the steel shell acting as the formwork. Such works require careful planning and site trials may be required to prove the practicality and effectiveness of the proposed solution.

Grouting

4.25 Grouting may be used to fill voids within the backfill and thereby stabilise a structure. Normally a sand/cement mix would be used where structural support was required. Where water is seeping into the structure or flowing through joints into the backfill it may be better to inject an expanding water reactive grout to provide a waterproof barrier. Relatively low injection pressures are usually employed to avoid disturbance to any surrounding structures, services and the overlying carriageway. Guidance on grouting is given in the Construction Industry Research and Information Association (CIRIA) report C514 by Rawlings et al (2000). In addition, guidance on the design and testing of grout mixes and on grouting operations is provided in TR 47 (Concrete Society, 1996). Care should be taken to ensure the grout does not pollute existing watercourses and penetrate drains and service ducts. The advice of the Environment

Agency and product manufacturers should be sought on the suitability of grouts used near watercourses.

MANAGEMENT OF ENVIRONMENTAL ISSUES

4.26 Where work is to be carried out on the structure, environmental issues such as fish migration and mammal ledges should be given consideration.

5. INDICATORS FOR PRIORITY OF REPAIR WORKS

GENERAL

5.1 The requirements for priority of repair works are clearly, in the main related to concerns about structural stability, i.e. safety issues. Such concerns might be prompted by the findings of a qualitative or quantitative review of the condition of a structure, i.e. an inspection or a structural assessment respectively. It is emphasised that analysis of structural stability of a CSBS is largely empirically based. Any fundamental differences in the findings of these two types of assessment should, therefore, be investigated prior to the commitment of funds for substantial repair works. To resolve any differences it might be necessary to determine the change in material or structural condition with time: this might require a reduction in the time interval between successive inspections, or the installations of instruments, or both of these. However, before accepting a delay in carrying out strengthening works, the risk and consequences of a collapse (partial or total) must be considered.

5.2 There are situations where priority repair work should be undertaken to avoid a reduction in level of service, i.e. serviceability issues, or expensive future maintenance work, i.e. economic issues. These issues mainly concern the material condition of a CSBS. Examples of these are:

(a) Serviceability:

- (i) where longitudinal differential settlement of a culvert leads to silting up of the invert, which in turn could lead to flooding upstream;
- (ii) where the breakdown of joint seals leads to seepage into an underpass and the subsequent ponding of water on the paving; this might produce a dangerous slippery surface - particularly in cold weather;

(b) Economy:

- (i) where a paving in a culvert has disintegrated to the point where the underlying metal is exposed to erosive and corrosive effects. In most cases the cost of repairing a paving is much less than the cost of repairing a badly corroded invert;

- (ii) similarly, usually the cost of repairing a secondary coating is much less than the cost of repairing a badly corroded galvanised steel shell.

5.3 Because the structural and material performance of a CSBS is a function of a number of site specific conditions, only general guidance on the need for priority repair work can be given. The following should, therefore, be viewed as a guide to good practice. The optimum timing and details of the required repair work vary somewhat from one CSBS to another, and are matters for engineering judgement. It is emphasised that a CSBS built to the requirements of BD 12 should be robust, i.e. it will be able to withstand relatively large ground movements and local damage without substantial loss of stability or serviceability.

STRUCTURAL INSTABILITY

5.4 Due to good practice in manufacture and installation, allied with sensibly robust specifications for durability in the UK, many of the following indicators of structural instability are fortunately rarely seen. Some would usually only occur during or shortly after construction but could potentially also develop due to the onset of corrosion, washout of backfill, or other changes in circumstance such as the effects of mining subsidence.

5.5 Some of the following indicators might occur in combination.

- (a) **Reverse curvature.** Such cases are rare in the UK, but without exception they require urgent consideration. (Such cases are also likely to occur shortly after construction.) Reverse curvature in the invert of a multi-plate pipe-arch caused by settlement of the surrounding embankment is shown in Figure 5.1a. The use of a mass concrete paving to repair flood relief structure that suffered from reverse curvature is shown in Figure 5.1b.
- (b) **Bolt failure.** This is a potentially catastrophic mode of failure, and investigations should be undertaken where there is bolt failure. Immediate strengthening around the area of a failed bolt should be considered as a matter of priority. (The loss of bolt through corrosion should not be

confused with bolts omitted during construction: not all the bolt holes in a CSBS need necessarily hold a bolt.)

- (c) **Excessive deviation from cross-section.** A structural analysis should be undertaken where the maximum deviation from the nominal cross-section exceeds the following:

Closed invert, circular structures	5 per cent
Closed invert, multi-radii structures	3 per cent
Arch structures	3 per cent

The findings of the analysis should dictate, by and large, whether or not priority repair work is required. Although the above are given in percentage terms, the severity of the problem, in terms of the consequences of failure and the cost of strengthening works, increases more than linearly with the span of the structure. Where distortion was introduced at the construction stage but the in-service structure seems stable, it might be worthwhile monitoring deformation with time. Structures that show any substantial increase in deflection require urgent consideration. Figure 5.2 shows some examples of excessive deviation due to poor construction practice. Construction practices in the UK are such that the likelihood of this type of problem occurring is remote.

- (d) **Tearing or shearing at bolt holes, local buckling, separation of joints/seams.** These mechanisms are all fairly definitive evidence that the shell of the structure is overstressed and, almost inevitably, immediate repair work is required.
- (e) **Deflection under live loads.** Any noticeable deflection (permanent or elastic) generated by the passage of a live load over a CSBS is another clear indicator that the structure is either under strength or has inadequate support from the surrounding ground. (There have been no reported cases of this occurring in the UK). Immediate consideration should be given to the structural stability and strengthening of a structure showing any signs of movement under live loads commonplace on the highway network. Figure 5.3 shows a local buckle in the crown of an experimental structure due to the passage of a heavy wheel load at low depth of cover – as might occur through unregulated or unsupervised movement of heavy plant during construction.

- (f) **Presence of voids in the backfill.** There are a number of mechanisms by which voids could form in and around CSBS, and they all threaten the stability of the structure. The most likely cause is the migration of fines into the CSBS. This might be identified by stockpiles of fines in the invert, but in culverts the fines might be washed away and here techniques such as tapping the steel shell to detect “hollow” areas, or ground-penetrating radar might be used. Voids might also be formed by wash out of material around the connection of side access gulleys; about one per cent of CSBS in the UK have such gulleys (Figure 5.4 shows that corrosion can occur preferentially around such features). In some cases it might be necessary to check the competence of the adjacent embankment, particularly the surface layers, and, in rare cases, the underlying soils. The presence of voids should be investigated as a matter of urgency.

MATERIAL CONDITION

5.6 The indicators for material condition are more subjective than for structural condition. Some of the following might occur in combination.

- (a) **Reduction in cross-section of the steel shell.** Immediate repair work is appropriate where a structural analysis shows that the structure is unsafe. The structural analysis should be based on the worst deteriorated section of the CSBS. Strengthening works might be required at a particular cross-section of the CSBS. Corrosion might occur at spot points or along the line of a CSBS in which case the structure might pass a structural assessment. It should be appreciated that the stability of a CSBS would not be compromised by some limited perforation of the steel shell. However, the fact that a structure passes a structural assessment does not mean that maintenance work is not warranted.

The decision for undertaking such works should take into account its cost, the likely lifetime of the repair, the higher cost of repairing or replacing the structure following further corrosion. Nonetheless, it would be prudent to plan maintenance and repair works where the thickness of galvanising has been reduced. It is far more effective and cheaper to maintain a structure, perhaps through the application of a secondary coating, before the galvanising has been lost than to attempt to refurbish a structure where corrosion is established.

- (b) **Loss of secondary coating.** An economic assessment should be made for undertaking maintenance work where the secondary coating has been removed over a continuous length or substantial area of a CSBS. As above, decisions on the extent and timing of any maintenance or repair work are a matter of engineering judgement.
- (c) **Seepage.** As above, the need and timing of the maintenance work is a function of the severity of the deterioration, the cost of the work and the economic and structural consequences of delaying the work. There might be over-riding service requirements for reducing or eliminating seepage into a structure. Seepage is commonly linked with corrosion of bolts and seams – these are considered below.
- (d) **Corrosion of bolts.** A structural assessment should be undertaken where there is heavy corrosion of bolts. (It is likely that corrosion would be more critical around a bolt hole than on a bolt.) Even where the findings of the assessment indicate that a CSBS is structurally sound, maintenance work should be put in hand where the effective strength of a bolt is less than about 75 per cent of its pristine strength.
- (e) **Seam corrosion.** This is often found in multi-plate structures. It is a potentially catastrophic failure mode and immediate attention should be given when the corrosion at a seam is particularly severe. It should be appreciated that, once initiated, corrosion is likely to continue unchecked and that the local rate of corrosion due to seepage of aggressive water can be particularly high.
- (f) **Deterioration of paving.** The timing of maintenance and repair work is a function of the severity of the deterioration of the invert. It would, of course, be a matter of priority where the paving was designed to provide structural support to the CSBS. Immediate repair work should be undertaken where the invert is substantially perforated or where water flows beneath the invert.

Whenever necessary and feasible, a paving should be repaired before it reaches a condition such that it requires complete replacement.

The timing and economy of maintenance and repair work should be considered where a paving does not contain peak flow: decisions might be based on various damage indicators defined above.

- (g) **Deterioration of ancillary structures.** Repair and maintenance works should be undertaken where the deterioration of ancillary structures such as side gulleys, aprons and headwalls permit the flow of water outside a culvert. The timing of the work is a function of the perceived scale of the problem, but they should not be postponed indefinitely.

Trash screens, drop inlets and catch pits should be maintained to ensure that they continue to operate as designed, and they should be replaced where they fail to operate as designed. This should be evident from an inspection of the devices and the condition of the invert.

5.7 Further guidance on deterioration of in-service CSBS is given in appendix E.



Figure 5.1a Reverse curvature in the invert of a multi-plate pipe-arch caused by settlement of the surrounding embankment (from SETRA, 1992)



Figure 5.1b Mass concrete invert placed into a multi-plate pipe-arch with reverse curvature in the invert

Figure 5.1 Reverse curvature in the invert and its repair



Figure 5.2a Excessive deflection of a multi-plate pipe-arch in France (from SETRA, 1992)



Figure 5.2b Partial collapse of a multi-plate pipe-arch in France (from SETRA, 1992)

Figure 5.2 Excessive deflections of CSBS due to poor construction practice



Figure 5.3 Reverse curvature - buckling due to excessive live loading at low depths of cover



Figure 5.4a Ceramic pipe entering close to the crown



Figure 5.4b Side entry gulley just above the paving

Figure 5.4 Corrosion around road drainage gulleys entering multi-plate pipe-arches

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7. ENQUIRIES

All technical enquiries or comments on this Advice Note should be sent in writing as appropriate to:

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APPENDIX A CSBS IN THE UK

GENERAL

A1 This Appendix provides information on the identification and determination of the physical properties of CSBS that have commonly been installed in the UK. The information given in Figure A1 and Tables A1 and A2 is intended to aid the identification and assessment of a CSBS but, wherever possible, reference should be made to manufacturers' data or to Highways Agency Type Approval Certificates. Definitions of some terms used in the following are given in Figure A2.

PRODUCT TYPES

A2 There are two common construction forms of CSBS to be found in the UK.

- (i) **Prefabricated pipes.** In the UK, riveted pipe used to be manufactured from curved corrugated sheets, riveted together at a factory, in lengths up to 20 feet (6.1m) and in diameters up to 6 feet (1.8m). However, such pipes have been superseded by helically wound pipe, which incorporate a lock seam, instead of rivets. These pipes are factory-made in lengths of 6m and in diameters of up to 3m. Manufacturers' trade names include Hel-cor and Helibore pipe. Consecutive lengths of both helically wound pipes and riveted pipes are joined using coupling bands.
- (ii) **Bolted segmental CSBS.** These are constructed from structural plates assembled on site to form round pipes, and multi-radial and arch structures. Trade names include Multiplate MP200 and T200. Although larger sizes are available, spans in excess of 8m are relatively uncommon on the UK trunk road and motorway network because they are not covered by BD 12

HISTORY

A3 The first CSBS was installed in the UK in 1914 beneath a railway at Hastings - it remains in service today. Further installations were infrequent until the 1930s when an American company (ARMCO) started to promote their products in the UK. The structures installed then were of relatively small diameter and

imported from the USA. In the mid to late 1940s, some bolted segmental structures were installed using war surplus material. In the 1950s, ARMCO built a factory at Newport, Gwent and following commissioning of the plant, the (then) Ministry of Transport was approached for approval for a range of products. In 1955, approval was given for the installation of CSBS of up to 4.5m diameter on all classes of highway. The Ministry accepted the use of the American Association of State Highway and Transportation Officials (AASHTO) specifications for all products including bitumen secondary protective coatings and invert pavings. These included the AASHTO M36, M167 and M190 Standards which at the time were the only widely accepted specifications covering the use of CSBS for highways. All CSBS were galvanised with a hot-dip zinc coating and in the UK the relevant standards covering steel manufacture and galvanising were used. The manufacturer's recommendations for bolted segmental structures included the installation of concrete paving having a minimum thickness of 50mm. At that time the Ministry did not make coatings or invert pavings obligatory, but they were actively promoted by ARMCO and, indeed, were used on the majority of installations in the UK.

A4 ARMCO remained the principal supplier of CSBS until the 1980s when a number of European manufacturers entered the UK market. These included Tubosider UK Ltd who set up a production facility in Warrington. Other manufacturers trading in the UK included an Italian-based company, Arc Sipra SRL, and a Swedish-based company, Galvan Fabrikant. In the mid-1980s ARMCO sold its European-based manufacturing plants as single national companies. In the UK, ASSET International Ltd purchased the Newport plant; Hamco Dinslaken Bausysteme GmbH the Dinslaken plant in Germany; and Finsider took over the ARMCO operation in Italy. In the 1990s ASSET International Ltd, Tubosider UK Ltd, Arc Sipra SRL, and Hamco Dinslaken Bausysteme GmbH obtained Department of Transport Type Approval Certificates for their CSBS systems.

A5 The first major motorway project where CSBS were installed in quantity was the Lydiate Ash to Quinton section of the M5, this section was constructed in the early 1960s. Another early motorway project where large numbers of CSBS were installed (to act as culverts) was the Trans-Pennine section of the M62.

Other motorways on which CSBS have been installed include the A1M, M1, M10, M11, M18, M180, M19, M20, M23, M25, M3, M4, M40, M42, M55, M56, M6, M69, M74, and M8. CSBS have also been installed on many dual and single carriageway roads.

DESIGN DOCUMENTS

A6 In 1982, the Department of Transport (DTp) issued its first Design Standard (BD 12) covering CSBS along with an accompanying Advice Note (BA 12). Durability requirements were addressed in these documents and a design life of 120 years was to be achieved through a combination of:

- an approved secondary coating
- a zinc coating
- a layer of sacrificial steel
- a paving to protect the invert of culverts

A7 The service life of the secondary coatings, and the rate of deterioration of the galvanising and sacrificial steel were all based on the in-service environmental conditions. Sacrificial steel was mandatory except for the interior surface of pipes which were classified as accessible and therefore deemed to be maintainable.

A8 The 1982 edition of BD 12 was applicable to bolted segmental and helically wound corrugated steel structures having spans ranging from 0.9 to 7.0m for circular and pipe arch profile structures, and from 2.0 to 7.5m for underpass² profile structures. BD 12 was revised and reissued in 1989 and the scope of that Standard was largely as defined in the 1982 issue except that now the span of structures ranged from 0.9 to 8.0m for circular and pipe arch structures, and 2.0 to 8.0m for underpass profile structures.

A9 BD 12 was revised again in 1995 and 2001³ and again the scope was largely the same as before but the categories of structure covered changed; specific mention of underpass profile structures was removed, but these documents now covered circular arch⁴

structures on concrete footings having re-entrant angles between 10° and 30°. The span of structures ranged from 0.9 to 8.0m for circular and multi-radii structures, and from 2.0 to 8.0m for circular arch structures.

A10 Efforts were made in successive editions of BD 12 to improve the durability of the structures. The need for improvement was evident from the performance of in-service CSBS. Structures installed prior to the introduction of BD 12 in 1982 were not designed with any sacrificial steel and despite the wide use of secondary coatings, some installations predating 1982 do not comply fully with current durability rules. All post-1982 structures can be assumed to have a sacrificial steel thickness on inaccessible surfaces, but this might not be the case for internal accessible surfaces deemed to be maintainable.

A11 The 1988, 1995 and 2001 editions of BD 12 required British Board of Agrément (BBA) certification of the multi-plate and helically wound construction systems (the certificates cover aspects affecting durability, such as coatings and invert pavings). Relevant certificates were

- ASSET International Ltd - BBA Certificates 90/R055 and 91/R059; coatings and invert pavings were based on the AASHTO M190 Standard
- Tubosider Ltd - BBA Certificate No. 91/R062; coatings were based on Monoguard and invert pavings on the AASHTO M190 Standard

COATINGS AND PAVINGS

A12 Since the 1950s hot-dip bitumen coatings and pavings conforming to the AASHTO M190 Standard have been used (the 1976 version of the Standard was adopted by the 1982 edition of BD 12). Until recently ASSET International Ltd (following their predecessors ARMCO) used the AASHTO M190 Standard for bitumen coatings for all their structures and also for invert pavings in their helically wound product as indeed did Tubosider Ltd in their helically wound product. The AASHTO M190 Standard requires, as a

² Underpass profile structures and pipe arch profile structures are both types of bolted segmental multi-plate structures. In the 1995 edition of BD 12 they have been combined together as multi-radii profile structures. The underpass profile structure has a high arch shape and a flat bottom making it particularly suitable for use as a pedestrian or vehicular underpass.

³ There were no accompanying Advice Notes to the 1989, 1995 and 2001 editions of BD12.

⁴ Circular arch structures had been constructed on the UK highway network up until the advent of the 1982 edition of BD12: they were most often used as flood relief structures.

minimum, a bitumen paving to cover 25 % of the circumference of a circular structure and 40 % of a multi-radii structure.

A13 Alternative cold-applied bitumen-based coatings have been used by ARMCO, and subsequently ASSET International Ltd. Coatings such as Trumble 5X and Bitumastic 50 were applied in the field. These provided a hard wearing coating with better abrasion resistance than hot-dip bitumen coatings to the M190 Standard, but these have since been withdrawn. Caution should be taken when refurbishing structures installed during the 1950s and 60s which have field-applied coatings because there is a very low risk that the coating may contain asbestos fibres: only a few structures were coated in this way. Subsequently, a product called Intex was used as a field-applied coating and also to refurbish damaged or worn areas on CSBS with hot-dip bitumen coatings to the M190 Standard.

A14 In the 1980s, Tubosider Ltd introduced a cold-applied modified bitumen-based protective coating called Monoguard, which was produced by Laybond Products Ltd. This was used on their helically wound product in conjunction with a bitumen paving.

A15 Other coating systems which were used occasionally in the UK include:

- (i) Epoxy coatings - for example the factory applied coating supplied by Hamco Dinslaken Bausysteme GmbH.
- (ii) PVC (polyvinyl chloride)-based plastisol coatings. Helically wound products used in Holland and parts of Germany are now commonly formed from plastisol coated steel, which is manufactured by Bergschenhoek BV in Zevenbergen, Holland.

A16 Both the hot-dip bitumen coating and paving used by ASSET International Ltd and the Monoguard coating and bitumen paving used by Tubosider had BBA Roads and Bridges Certificates. However, following the introduction of the 1995 edition of BD 12, which did not require the application of a secondary protective coating, both manufacturers (in most cases) relied solely on the life of the sacrificial steel and zinc coating to provide an adequate service life for their products. The 2001 edition of BD 12 required secondary protective coatings to be applied to each face.

A17 Concrete pavings of 50mm thickness (above the crest of the corrugation) were also recommended by

ARMCO and this was adopted in the 1982 edition of BD 12. The subsequent editions of BD 12 increased the thickness of the concrete paving to a maximum of 170mm under high flow conditions where waterborne solids exceed 100mm in size. The rules governing concrete strength, reinforcement size and layout, depths of cover, and the requirements for construction joints were given in each edition of BD 12. A concrete paving to the specification given in BD 12 was the only alternative to a hot-dip bitumen paving, although the 1982 version of BA 12 provided some alternative ideas for invert protection.

DATA

A18 The following figures and tables provide a concise reference guide for the identification and properties of CSBS likely to be encountered in the UK. Figure A1 shows the range of shapes and structural types. Table A1 provides information on the range of sizes, plate thicknesses and shapes for each corrugation type. Table A2 details the properties for each corrugation type and bolt/rivet or lock seam arrangement.

Bolts and rivets

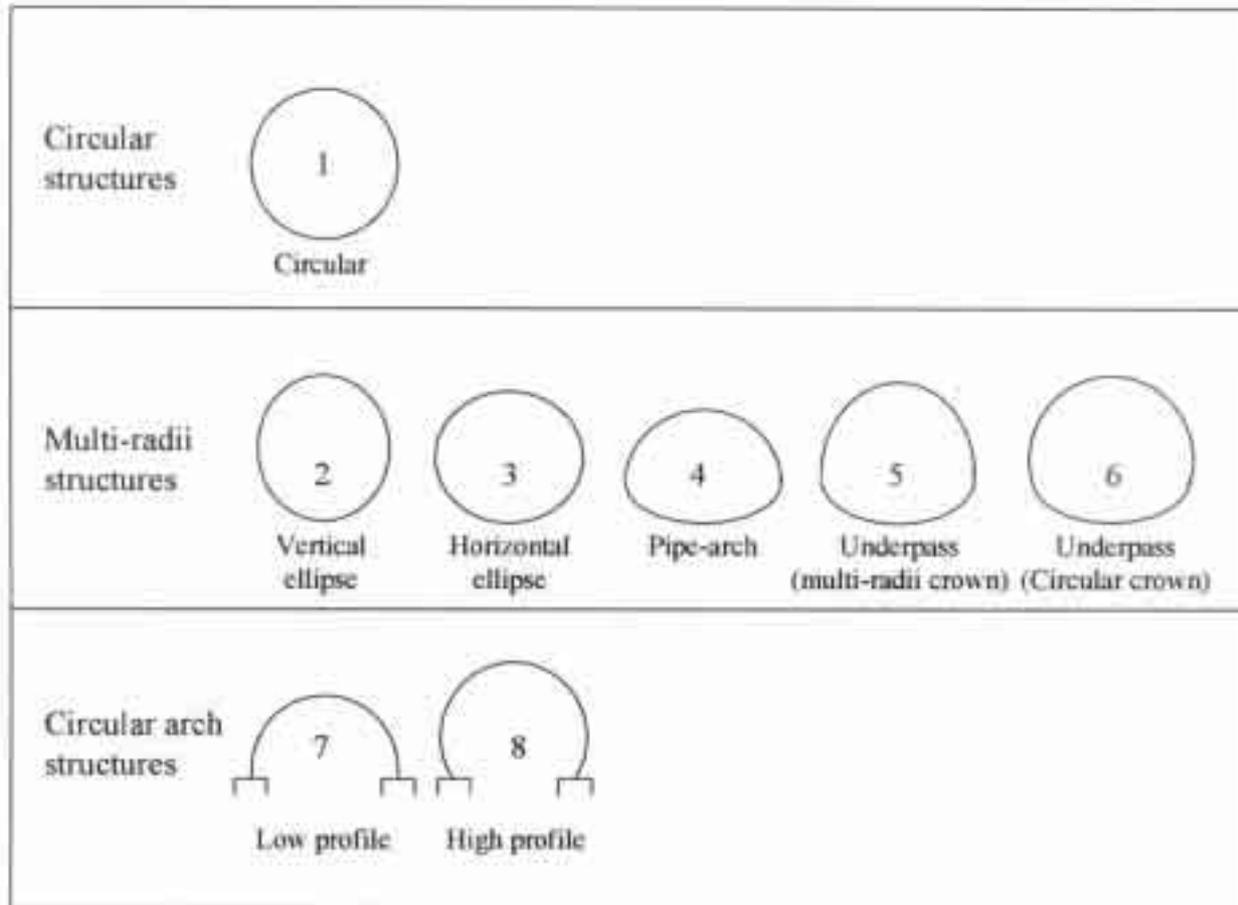
A19 Riveted pipe formed from 2 2/3" x 1/2" (68 x 13mm) corrugated steel plate used 5/16" (7.9mm) cold-driven rivets for plate thicknesses of 0.064" and 0.079" (1.5 and 2.0mm), and 3/8" (9.5mm) rivets for plate thicknesses of 0.109", 0.138" and 0.168" (2.7, 3.5 and 4.2mm). Longitudinal seams are riveted with two rivets per corrugation but pipes 42" or larger in diameter are double riveted with 4 rivets per corrugation.

A20 CSBS formed from bolted segmental plate utilise either grade 8.8 or grade 10.9 steel bolts. These high tensile steel bolts were used to ensure that the seams failed through distortion and tearing of the plates around the bolts rather than through bolt failure. Grade 10.9 bolts were used for the heavier plate thicknesses where higher seam strengths are developed. A variety of bolt, nut and washer configurations have been used. The heads of the bolts may be shaped to fit the profile of the corrugation, or to facilitate the tightening of the nuts and bolts from the inside of the structure without need to access the soil side, i.e. so that the final re-torquing of the bolts can be carried out after the completion of backfilling. With some configurations, washers were placed below the nuts and bolt heads to prevent damage to coatings during assembly. Later structures used 'Euro' bolts where the bolt heads were

designed to grip the plates to allow torquing without access to the soil side: this facilitated rapid assembly as well as improving seam strength. The nuts to 'Euro' bolts incorporate a profiled flange shaped to provide close contact with the structural plates and to reduce damage to coatings. Where nuts of this type are found in a structure then invariably it was assembled with 'Euro' bolts.

A21 Where the manufacturer of the structure is not known, it may be possible to identify them by considering the bolt head markings.

Profiles of short-span structures (spans less than 8 metres)



Profiles of larger structures incorporating thrust beams

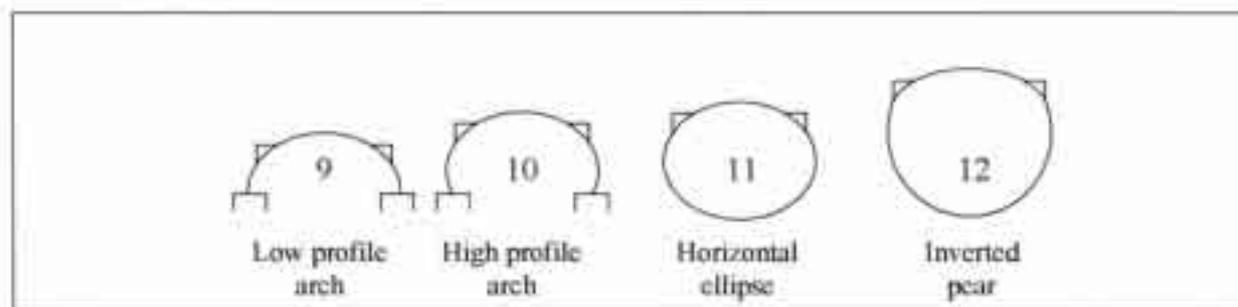


Figure A1 Typical profiles of CSBS commonly installed in the UK

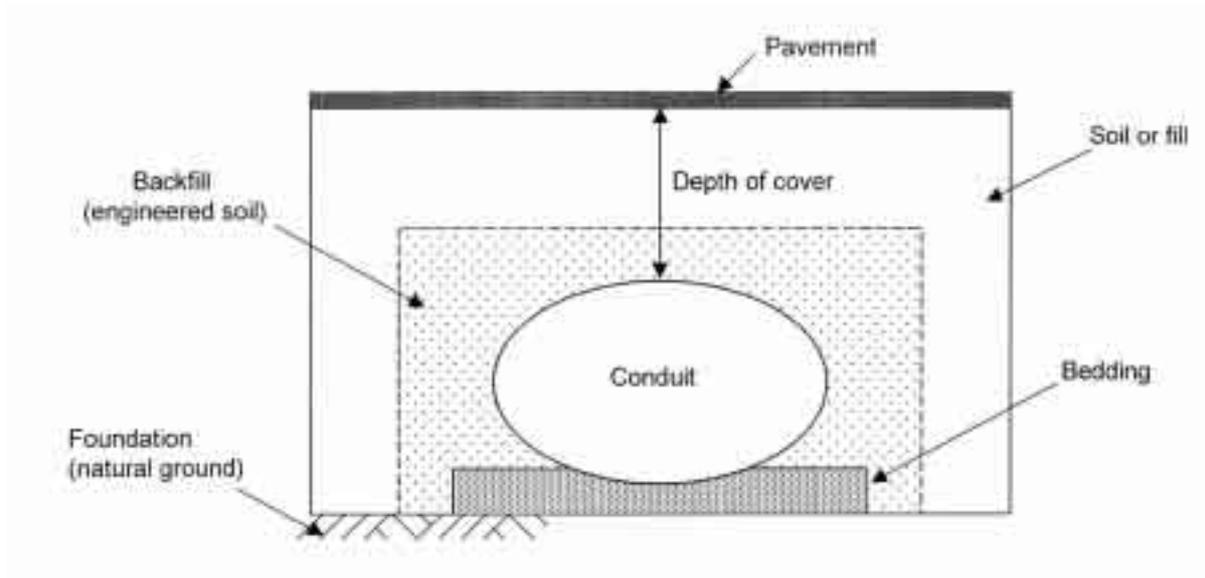


Figure A2(a) Terminology relating to surrounding fill and soil

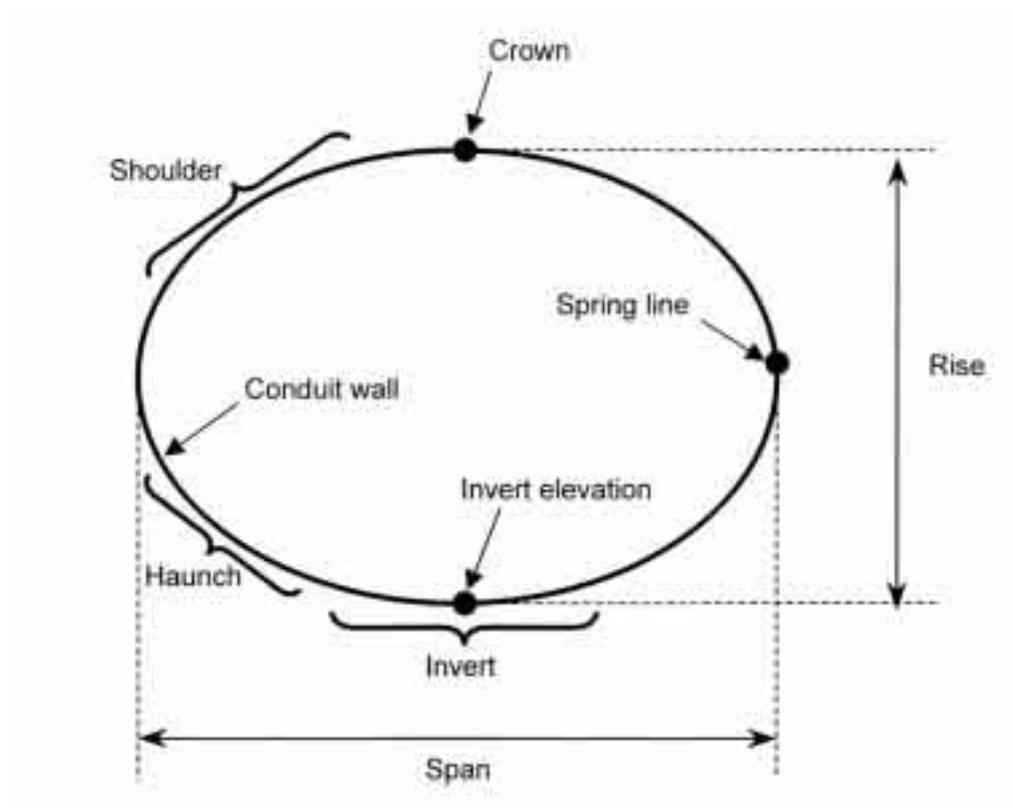


Figure A2(b) Terminology relating to the cross section of closed invert structures

Figure A2 Definition of terms for CSBS (part 1 of 3)

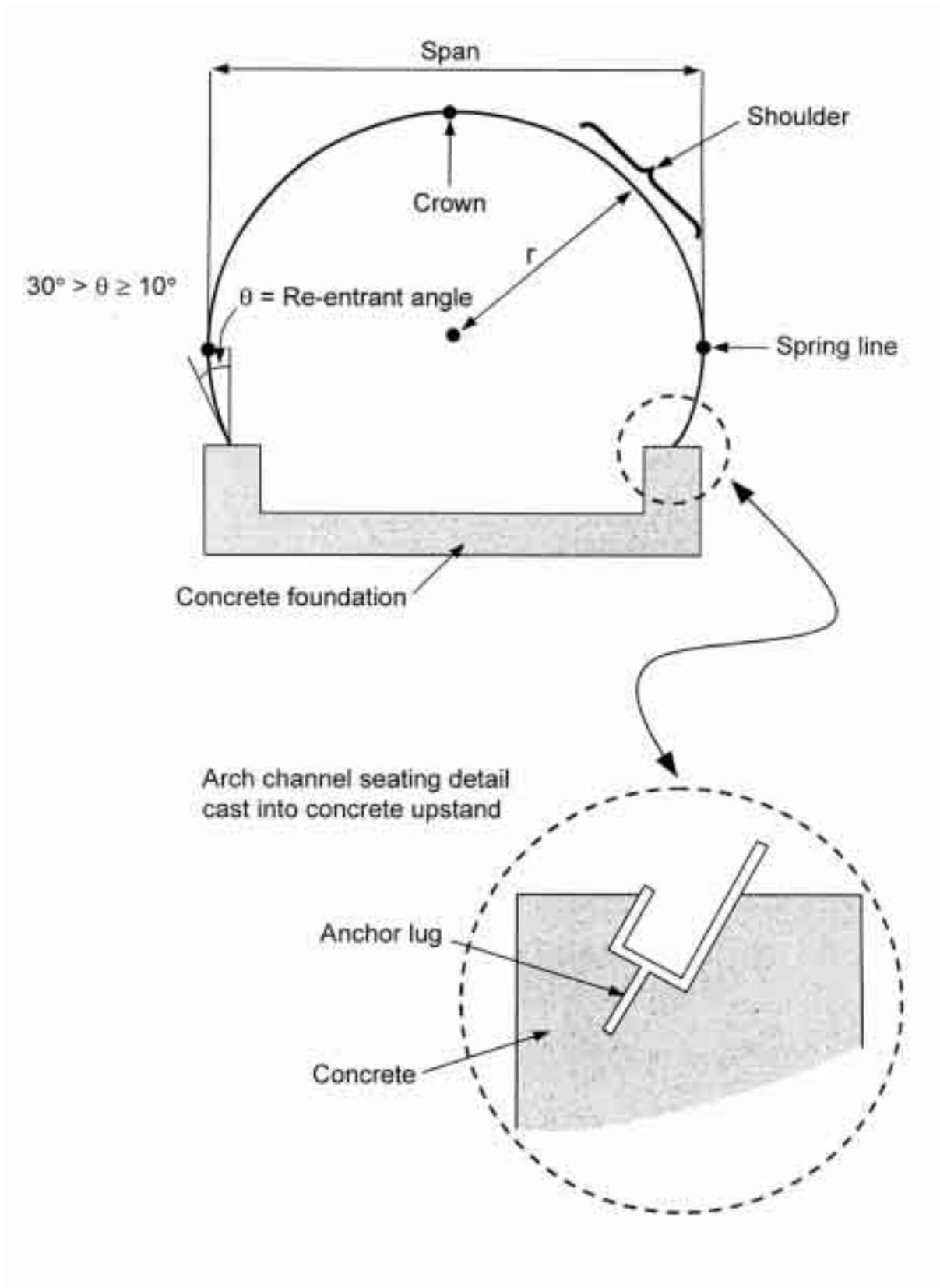


Figure A2(c) Terminology relating to the cross section of arch structures

Figure A2 Definition of terms for CSBS (part 2 of 3)

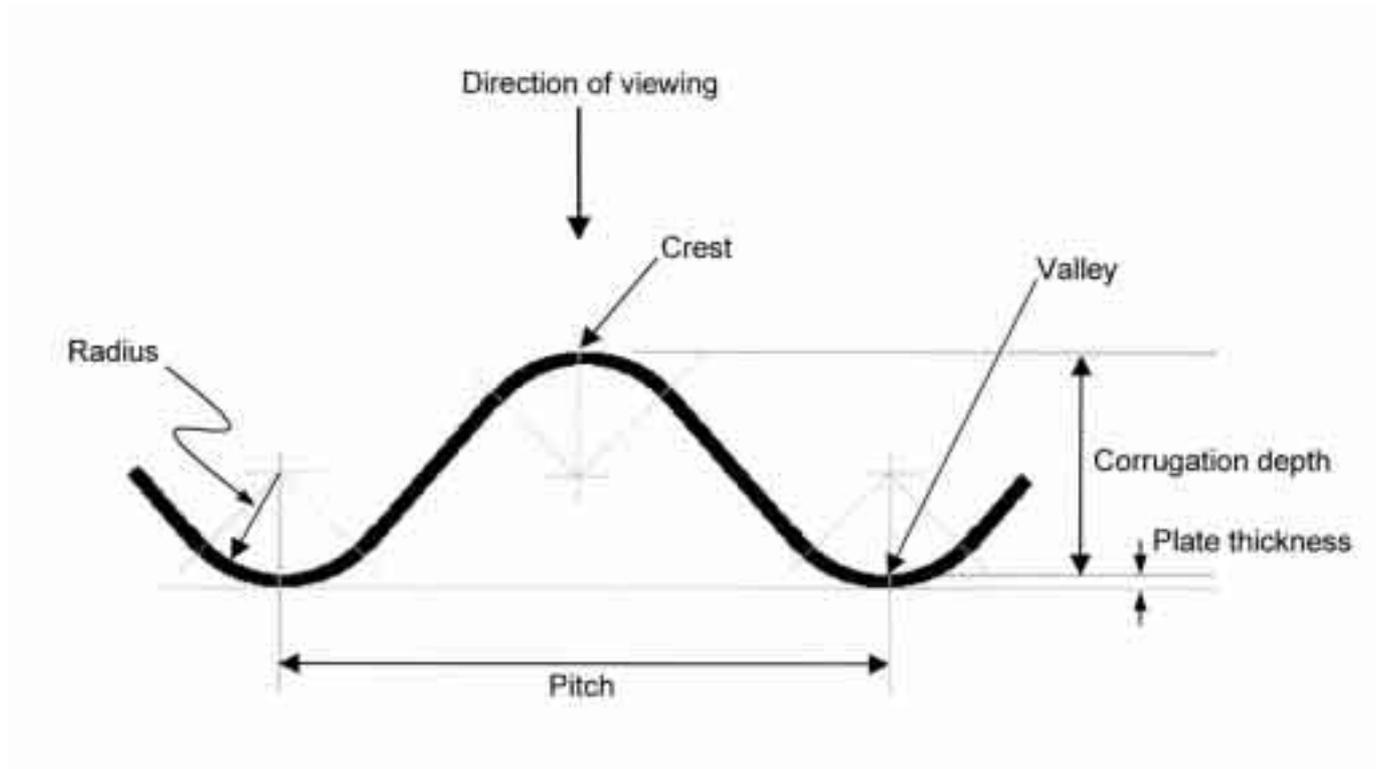


Figure A2(d) Terminology relating to the corrugation profile

Figure A2 Definition of terms for CSBS (part 3 of 3)

Corrugation size mm (Imperial units)	Approximate range of spans metres (Imperial units)	Thickness range of steel plate mm (Gauge size)	Shape see Figure A1
Riveted – prefabricated 20 ft (6.0 m) standard lengths			
68 x 13* (2 2/3" x 2")	0.9 - 1.8 (36" - 72")	1.5, 1.9, 2.7, 3.4, 4.2 (16, 14, 12, 10, 8 gauge)	1 & 4
Spirally corrugated lock seam – normally supplied in 6.0 m lengths			
68 x 13	0.9 - 1.2	1.5, 2.0, 2.5, 3.0, 3.5	1
100 x 20	0.9 - 3.0	1.5, 2.0, 2.5, 3.0, 3.5	1
125 x 25	1.2 - 3.6	1.5, 2.0, 2.5, 3.0, 3.5	1
Bolted			
68 x 13	0.9 - 2.0	1.5, 2.0, 2.7, 3.5	1 & 4
100 x 20	0.9 - 3.0	1.5, 2.0, 2.5, 3.0, 3.5	1 & 4
100 x 22	0.9 - 3.6	1.5, 2.0, 2.5, 3.0, 3.5	1 & 4
152 x 32	1.2 - 3.5	2.0, 3.0, 4.0	1 & 4
152 x 51* (6" x 2")	1.5 - 7.0 (5' - 24')	2.7, 3.5, 4.2, 4.7, 5.5, 6.2, 7.0 (12, 10, 8, 7, 5, 3, 1 gauge)	1 - 7, 9 - 12
200 x 55	3.5 - 12.0	2.75, 3.25, 4.0, 4.75, 5.5, 6.25, 7.0, 7.75, 8.0	1 - 12

* Denotes product originally manufactured to Imperial dimensions

Table A1 Identification of common types of CSBS

Note: The gauge thicknesses given above are based on the US Standard Gage for Sheet and Plate Iron and Steel (Black) as established by Act of Congress, July 1, 1893 (with revisions, 1945). The metric values provided above are the nominal thickness of ungalvanised steel plate as produced in the UK. Wrought iron plates will be thicker than steel plate for an equivalent gauge thickness. A more exact conversion from the US Standards Gage to the metric equivalent for both galvanised and ungalvanised steel plate is provided in the handbook of the American Iron and Steel Institute (AISI, 1993).

Corrugation size mm (Imperial size)	Thickness mm (Gauge size)	Area of section mm ² /m	Moment of inertia mm ⁴ /mm		Nominal seam strengths		
					kN/m		
68 x 13 (2 2/3" x 2") Connection types: M12 bolts: 5/16" rivets on 16 _{Ga} & 14 _{Ga} : 3/4" rivets on 12 _{Ga} to 8 _{Ga}	1.5 (16 _{Ga})	1620	31		1.5 bolts/corr	2 rivets/corr	4 rivets/corr
	1.9 (14 _{Ga})	2160	41		173	244	315
	2.7 (12 _{Ga})	2917	57		249	266	435
	3.5 (10 _{Ga})	3783	76		466	342	683
	4.2 (8 _{Ga})	4515	94		573	358	715
100 x 20	1.5	1641	80	*	1 bolt/corr	1.5 bolts/corr	2 bolts/corr
	2	2188	107	S A	- 227 (M16)	336 (M14) -	437 (M14) 425 (M16)
	2.5	2736	135	S A	- 261 (M16)	488 (M14) -	622 (M14) 472 (M16)
	3	3284	164	S A	- 323 (M16)	609 (M14) -	779 (M14) 602 (M16)
	3.5	3832	193	S	- 486 (M16)	760 (M14) -	985 (M14) 888 (M16)
100 x 22 Connection type: M14 bolt; Grade 8.8	1.5	1660	91		1.5 bolts/corr	2 bolts/corr	
	2	2210	123		330	430	-
	2.5	2770	153		530	690	-
	3	3320	186		734	952	-
	3.5	3880	219		765	1038	-
					938	1220	-

* Products of the following manufacturers:

S Arc Sipra SRL (formerly ARMCO Finsider)

A ASSET International Ltd (formerly ARMCO)

Note: The seam strengths quoted are derived from Type Approval Certificates (DTp, 1991 to 1996) or where appropriate manufacturers' literature. Where a product has been produced by more than one manufacturer then the lowest seam strength value has been quoted.

Table A2a Data for CSBS commonly installed in the UK

Corrugation size mm (Imperial size)	Thickness mm (Gauge size)	Area of section mm ² /m	Moment of inertia mm ⁴ /mm	Nominal seam strengths kN/m		
125 x 25	1.5	1660	143	This corrugation only currently available in spirally corrugated lock seam pipe		
	2	2210	191			
	2.5	2760	240			
	3	3320	289			
	3.5	3875	337			
152 x 32 Connection type: M16 bolt				3 bolts/corr	4 bolts/corr	
	2	2210	281	568	710	
	3	3317	425	961	1272	
	4	4424	573	1375	1830	
152 x 51 (6" x 2") Connection type: M19 bolt; Grade 8.8 up to 4.7 m span, and Grade 10.9 up to 7.0 m span				2 bolts/corr	4 bolts/corr	Notes
	2.7 (12 _{Ga})	3348	1007	890	-	Imperial product, but produced as an equivalent metric product by Arc Sipra SRL
	3.5 (10 _{Ga})	4343	1313	1232	-	
	4.2 (8 _{Ga})	5215	1585	1609	-	
	4.7 (7 _{Ga})	5838	1782	1689	-	
	5.5 (5 _{Ga})	6836	2101	1994	2944	
	6.2 (3 _{Ga})	7711	2385	2204	3540	
	7.0 (1 _{Ga})	8711	2715	-	3664	

Note: The seam strengths quoted are derived from Type Approval Certificates (DTp, 1991 to 1996) or where appropriate manufacturers' literature. Where a product has been produced by more than one manufacturer then the lowest seam strength value has been quoted.

Table A2b Data for CSBS commonly installed in the UK

Corrugation size mm	Thickness mm	Area of section mm ² /m	Moment of inertia mm ⁴ /mm		Nominal seam strengths		
					kN/m		
200 x 55 Connection type: M20 bolts: Grade 8.8 or 10.9	2.75	3248	1242	*	2 bolts/corr	3 bolts/corr	4 bolts/corr
				A T H	582 517 -	657 684 774	719 - 937
	3.25	3840	1471	A T H	752 680 -	819 822 1029	934 - 1278
					4	4729	1819
	4.75	5618	2171	A T H			
					5.5	6509	2526
	6.25	7401	2886	A T H			
					7	8293	3251
	8	9490	3745	T			

* Products of the following manufacturers:

A ASSET International Ltd (formerly ARMCO)

T Tubosider United Kingdom Ltd

H Hamco Dinslaken Bausysteme GmbH

Note: The seam strengths quoted are derived from Type Approval Certificates (DTp, 1991 to 1996) or where appropriate manufacturers' literature. Where a product has been produced by more than one manufacturer then the lowest seam strength value has been quoted.

Table A2c Data for CSBS commonly installed in the UK

APPENDIX B TYPES OF INSPECTION

B1 *Superficial Inspections* are cursory checks for obvious structural deficiencies which require urgent attention so as to avoid accidents or subsequent high maintenance expenditure. With CSBS such inspections should, for example, identify gross deformation, severe corrosion, damage to the head walls, paving or invert and protective gates of a culvert, and the blockage or scour of material at the inlet and outlet of a culvert.

B2 *General Inspections* require a visual examination of all parts of a structure not requiring special access measures, and of adjacent earthworks and watercourses which could affect the stability of the structure. Such inspections should be carried out within two years of the last General or Principal Inspection. Such inspections will highlight areas where such coatings are damaged or missing.

B3 *Principal Inspections* require a close visual examination of all the parts of a structure and adjacent earthworks and watercourses that can be inspected and defects recorded in detail. Such inspections should be carried out at intervals agreed with the Overseeing Organisation. Some simple testing of concrete condition may, however, be agreed.

B4 *Special Inspections* involve a detailed assessment of a defect identified in previous inspections by further testing or measurement or a review of the condition of a structure, or part of a structure, following unusual in-service conditions. Such inspections may, for example, be undertaken following:

- (i) flooding in the area of the structure;
- (ii) the passage of an abnormal heavy load on the overlying carriageway - prior notification of the movement of such a load should be received;
- (iii) a major incident such as chemical spillage or fire adjacent to the structure;
- (iv) excessive settlement including mining subsidence; and
- (v) as a follow up to a previously reported problem such as the breakdown of the protective coatings.

Special Inspections might necessitate the use of equipment and techniques not normally used for the other inspections so that structural stability can be assessed and a decision reached on the necessity for repair or replacement work. For example, it may require the use of a portable rotary cutter to recover cores from the sides of a structure.

Special Inspections to provide data for structural assessments may include such inspections and measurement additional to a routine Principal Inspection. Alternatively, those additional inspection and measurements required for an assessment for inspection may be added to a planned Principal Inspection.

B5 *Acceptance Inspections* are required to identify and record any work that is outstanding under a contract and to agree which items of work must be completed before the MA takes over the responsibility for maintaining the structure.

APPENDIX C EXAMPLES OF SUMMARY REPORT FORMS AND SKETCHES FOR RECORDING DATA

SUMMARY FORM

C1 Table C1 provides a form for recording basic information on the structural and material condition of a structure. A comparison of successive forms should allow the rate of deterioration to be assessed.

SKETCH

C2 Figure C1 is the type of diagram that may be reproduced in a Principal or Special inspection report. Areas of deterioration should be highlighted and descriptive notes added to the sketch.

Notes: Appendix C is not applicable where SMIS is used.

In Scotland, the form of PI reporting is as required in the Trunk Road Bridges Database and a general arrangement drawing detailing where photographs are taken, headroom and orientation etc is required to be submitted with each PI report.

Structure Key and Number		Location	
Grid Reference		Maintenance since last Inspection?	
Date and Type of Inspection			
Inspected by		Signature	
Nominal span / width (m)	Nominal headroom (m)	Nominal length (m)	

STRUCTURAL DEFECT	Assessment and comment	Severity *	Extent *
Visible longitudinal settlement?	Y/N		
Joint separation ?	Y/N		
Voids in backfill?	Y/N		
Visible change in cross-section?	Y/N		
Reverse curvature?	Y/N		
Significant deviation in profile?	Y/N		

MATERIAL CONDITION	Location	Range of thickness	Severity *	Extent *
Paving				
Type	Invert			
Size (% of periphery)				
Secondary coating	Crown			
Type	Wet/dry line			
As-built thickness (µm)	Invert			
	Ends/other			
Zinc	Crown			
	Wet/dry line			
As-built thickness (µm)	Invert			
	Ends/other			
Steel	Crown			
	Wet/dry line			
As-built thickness (mm)	Invert			
	Ends/other			

* For severity and extent of deterioration use categories given in BE 11/94 in BD63 (DMRB 3.1.4)

Table C1 Form for recording information on structural and material condition

Note: not applicable where SMIS is used.

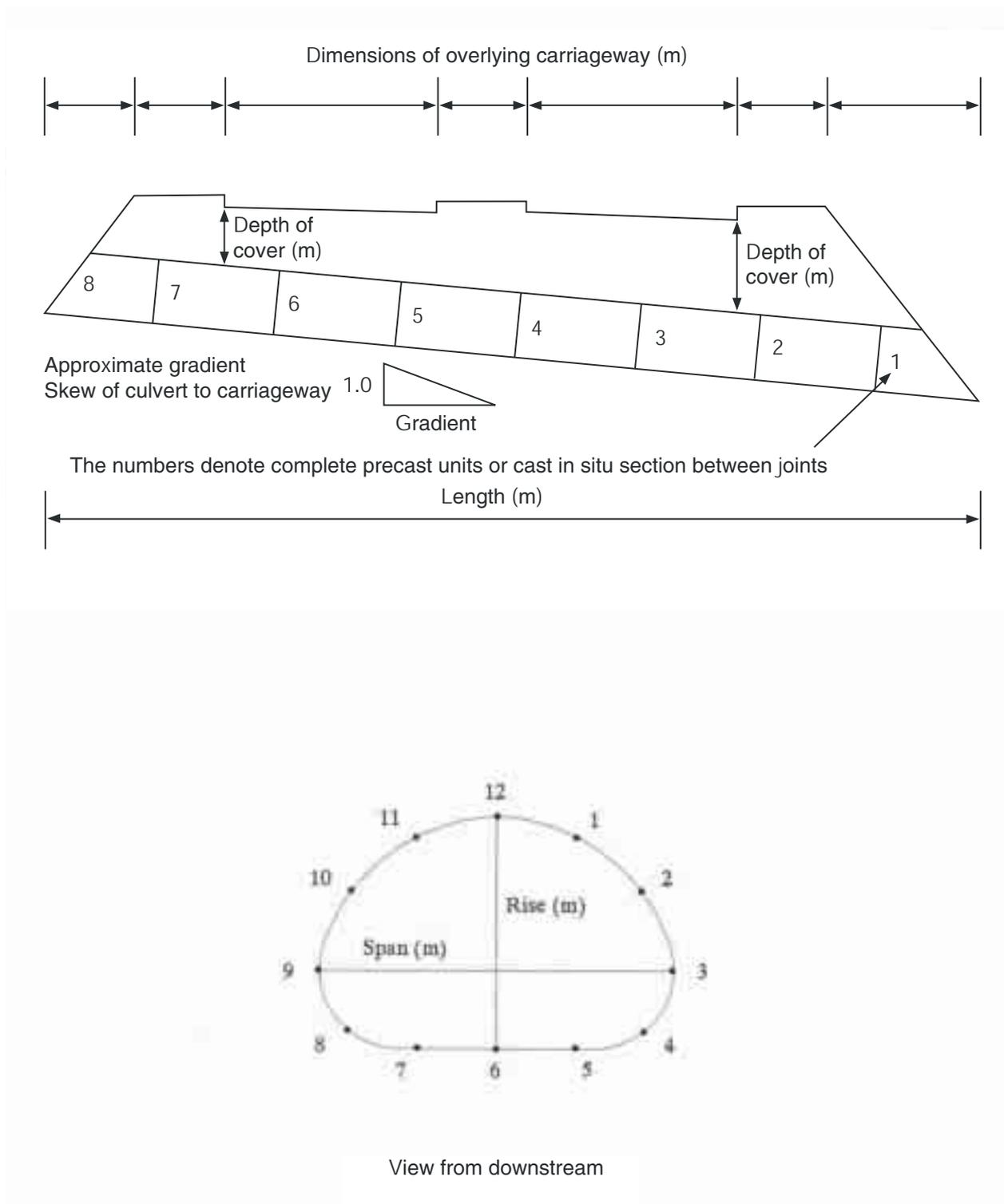


Figure C1 Sketch for record keeping purposes

Note: not applicable where SMIS is used.

APPENDIX D GUIDANCE ON STRUCTURAL ASSESSMENT OF CSBS

ASSESSING STABILITY

Design

D1 A level of safety may be introduced into structural design by, for example, the incorporation of global or partial safety factors. BD 12 adopts a partial factor approach to design, in which the values of the various applied loads and strengths of the structural components are individually factored to account for possible deviations from their assumed characteristic or nominal values⁵.

D2 For example, the nominal value of a particular load is multiplied by a partial factor (γ_n) the value of which should account for the possibility of the load exceeding its nominal value during the life of the structure. Similarly, the value of the partial factor applied to the strength of a particular component (γ_m) should reflect the possible variation of the strength of the component from its assumed characteristic value, as derived from tests on control specimens. (Note that γ_m is not intended to cover for the deterioration of the structural integrity of a component.) The factored values of the nominal loads and strengths are referred to as *design* values.

D3 The effects of the design loads on CSBS are expressed in terms of, for example, hoop stresses. The design load effects are multiplied by a partial factor (γ_{f3}) to account for inaccurate assessment of the effects of loading, unforeseen stress distributions within the structure, and variations in the dimensional accuracy achieved in construction. Whilst it is difficult to see how values of γ_{f3} might accurately account for each of these factors, in practice the application of this partial factor can be viewed as covering the uncertainties associated with the calculation model.

D4 For the design of CSBS, values of γ_{fL} and γ_{f3} are provided in Tables 3.1 and 4.1 respectively of BD 12/01, and values of γ_m are given for soil and steel in Chapters 5 and 6 respectively of that Standard. (The empirical nature of the design of a CSBS is evidenced by the rather high values of γ_{f3} given in Table 4.1.)

Assessment

D5 The design process in BD 12 results, quite sensibly, in conservative solutions. This is necessary because of the level of uncertainty associated with the imposed loading at the design stage, and because the model has to be valid for a range of structural forms, spans, and installations across the UK. However, many of these uncertainties are removed when assessing the stability of an in-service structure, and an overly conservative assessment may lead to costly and perhaps unnecessary strengthening works, or even the replacement of a structure. Thus, notwithstanding the recommendations in clause 3.7 of BA 55/00, it is desirable to adopt less severe and more realistic loading criteria and material parameters when assessing a structure. For example, much of the uncertainty associated with design of a CSBS is removed by its successful construction. If the structure is stable, it may be assumed that it is acting as a ring in compression and is able to support the required loads. In this situation what is required is an assurance that an acceptable margin of safety exists.

D6 For assessment purposes, a less onerous loading regime may be adopted by reducing the γ_n values applied to the superimposed dead load and live load to unity (i.e. using the nominal loads for assessment). Although this may appear unconservative, it should be borne in mind that the nominal loads defined in BD 12 are quite severe for the following reasons:

⁵ In a limit state partial factor approach to design, the applied loads and the strengths of materials or components are usually expressed as characteristic values which may be defined statistically. Typically a characteristic load will have a 5 per cent chance of being exceeded, i.e. most of the loads will be less than the characteristic load, whilst a characteristic strength will have a 95 per cent chance of being exceeded, i.e. most of the strengths will exceed the characteristic strength. However, where there are insufficient data to define characteristic values, loads and strengths are often expressed as *equivalent nominal* values, which are derived from available data or based on engineering judgement. Because of the difficulties associated with determining loads statistically, most of the loads given in BD 37 (DMRB 1.3) and BD 12 are nominal loads.

- (i) The superimposed dead load is calculated for a depth of cover which is greater than the distance between the crown of the structure and the top of the road surface. This is particularly conservative for larger span structures.
- (ii) The vertical live load is calculated for the crown of the structure, and taken to act across the whole span. Again this is a conservative assumption because the dispersed live load decays with depth and would not be as onerous across the whole span of the structure as at the crown.
- (iii) The nominal HB axle load of 45 tonnes is far heavier than any axle load ever likely to traverse a CSBS. (Depending on the age of a structure and the class of road, some structures might have been designed to support 30 or 37.5 units, i.e. tonnes, of HB load.) The abnormal load model was derived in the late 1940s and is not representative of modern abnormal loads, which tend to have lighter, but more numerous, axles. Similarly, the HB vehicle (with bogies separated by the minimum specified distance of 6.0m) represents a more concentrated loading than almost all known abnormal load movements.

D7 As discussed in D4 above, the values assigned to the partial factor γ_{f3} in Table 4.1 of BD12/01 show that, in some cases, there is considerable uncertainty associated with the determination of the effects of the applied loads on CSBS. It is therefore prudent to maintain these values for assessment, even though they may appear overly conservative. Similarly, the values of γ_m for soil and steel given in BD 12 should also be maintained for assessment purposes. In short, the actual level of safety of an in-service CSBS cannot be determined particularly accurately, and the considerations covered by D8 to D17 determine the minimum (calculated) level of acceptance.

ASSESSMENT CONSIDERATIONS

D8 The structural assessment of an in-service CSBS is largely subjective, but the following should be considered when assessing the need for strengthening works:

- (i) the shape of the structure;
- (ii) material condition;
- (iii) the loading on the structure;
- (iv) the importance and purpose of the structure;
- (v) the consequences of continuing deflection and, ultimately, of taking the structure out of service; and
- (vi) the consequences and the cost of replacing the structure.

D9 A CSBS should be assessed for the same limit modes defined in BD 12, i.e. checks should be made to ensure that the assessed compressive hoop stress does not exceed suitably factored values of:

- (i) the minimum yield strength of the steel;
- (ii) the nominal buckling strength; and
- (iii) the seam strength of the structure.

General guidance on assessing CSBS is given in the following and an example of an assessment calculation follows in D18 to D29.

D10 **Yield strength.** In the absence of contrary information, for the UK a minimum yield strength of 230N/mm² should be assumed for the steel used for CSBS.

D11 **Buckling stress.** It is difficult to accurately determine the capacity of a CSBS to resist buckling but it is unlikely to be critical except for larger structures or those that are badly distorted. It should be noted that a change in the thickness of the steel plate (due to corrosion) or to the shape and amplitude of the corrugations (through differential settlement or mining subsidence) will affect the moment of inertia (I) of the corrugated steel sheet about its neutral axis⁶. Moreover, the value of I will not necessarily vary in a simple linear manner with the degree of corrosion. For example, corrosion along the peaks and troughs of a corrugation will reduce the value of I to a much greater extent than corrosion closer to the neutral axis. With regard to changes in the shape of a corrugation, an extension in the length of corrugation will reduce the

⁶ The term 'moment of inertia' is used in this Advice Note for continuity with BD12 but strictly speaking the term 'second moment of area' should be used.

amplitude and also the cross-sectional steel area per metre run; both of which will reduce the value of I . Conversely, a reduction in the length of corrugation will result in an increase of the value of I . Again the value of I will not vary in a simple manner with the degree of extension or compression of the corrugation. For some corrugation profiles an extension in corrugation length of one per cent would lead to a reduction in the value of I of about three per cent, but for others the reduction may be closer to ten per cent. Accurate measurement of the section profile in the field and calculation of the actual I value may be necessary where a structure is close to failing the buckling check, or has suffered substantial settlement. Mining subsidence will tend to be a bigger problem than differential settlement because hogging ground strains will increase the tension at the crown of a structure. With differential settlement, the hogging strains are likely to be near the ends of the structure where embankment loads and live loads are lower.

D12 Seam strength. The residual seam strength need only be checked where the strength has been seriously impaired along a continuous and substantial length of a structure. (Information on the wall thickness and geometries of the various types of structure commonly installed in the UK is provided in Appendix A.)

D13 Shape. An assessment can be based on the profile of the 'worst case' cross-section.

D14 Material condition. For assessment purposes, the assumed thickness of the steel shell may be based on the measured minimum thickness of steel in a corroded area that represents a substantial part of the structure. This should be used to determine the residual area of the section (a_r) that is required to determine the assessment hoop stress.

D15 In completing an assessment it is necessary to consider the likelihood and effects of further material deterioration. Even if the structure is considered sound it may well be necessary to refurbish the coatings and, if appropriate, to provide a paving. These actions may be necessary to maintain or improve the existing structural (and material) condition. It is important that measurements of the thickness of the steel and protective coatings are recorded in such a way that changes between inspections can be readily identified.

D16 Loads. The compressive hoop load (C_{ass}) in the wall of a structure may be determined in accordance with method given in BD 12 for determining the design compressive hoop load (C) but, as discussed in D6, with nominal values being used for the superimposed dead

load and vertical live load. The best estimate of the 'worst case' assessment hoop stress, $f_{a(ass)}$, can be determined from the compressive hoop load (C_{ass}) and the residual area of section (a_r).

D17 Consequences of failure. The consequences of failure of a CSBS should always be taken into account when interpreting the findings of an assessment. For example, the failure of a large span structure with a shallow depth of cover is more likely to affect the overlying roadway (and thus impact on the safety of road users) than the failure of a smaller structure at some depth.

EXAMPLE CALCULATION

D18 The numerical checks outlined below are relatively simple and should not in any way replace engineering judgement regarding the condition and safety of a structure. Guidance on the procedures that should be followed when a structure fails an assessment is given in 3.35.

D19 Structure details. Details of the structure can be obtained from 'As-built' records, field measurements, or from the tables provided in Appendix A.

D20 The following example is provided for a structure installed through an embankment on the trunk road network (i.e. it is assessed for 45 units of HB loading). The structure is a bolted segmental closed circular structure, with a radius of 1.5m, and a depth of cover at the crown of 1.0m. The structure has a corrugation size of 152mm x 51mm (6" x 2"), with 2 bolts/corrugation, and a plate thickness of 3.5mm (see Table A2b).

D21 Procedure. The first step is to calculate the hoop load (C_{ass}) and use this to determine the hoop stress, $f_{a(ass)}$. The assessment hoop stress (i.e. the hoop stress multiplied by the appropriate value of γ_{f3}) must not exceed either the minimum yield strength or the buckling strength (both divided by their appropriate values of γ_m). Similarly, the assessment hoop load (i.e. the hoop load multiplied by the appropriate value of γ_{f3}) must not exceed the estimated residual seam strength of the structure, $f_{s(res)}$.

Hoop load, C_{ass}

D22 From field observations of the cross-section of the 'worst-case' profile, establish the span of the structure and the depth of cover over the crown. In this example the span (S) is 3.0m and the crown of the structure is 1.0m below the surface of the road pavement.

$$C_{ass} = [S (P_d + P_L)]/2$$

where S = span (m) = 3.0m,

P_d = nominal superimposed dead load,

P_L = nominal vertical live load

Dead load, P_d

D23 The assessment dead load may be calculated from the height of fill above the crown and the geometry of the structure.

$$P_d = \gamma h$$

where γ = bulk unit weight of backfill: a value of 20kN/m³ has been assumed,

h = depth of cover (m). The method used to determine h is dependent upon the shape of the structure (see Clause 3.2 of BD 12/01). For this example:

$$h = h_t + 0.25 r$$

where h_t = the depth of cover over the crown = 1.0m

r = the radius of the structure = 1.5m

$$h = 1.0 + (0.25 \times 1.5) = 1.375\text{m}$$

$$P_d = 20 \times 1.375 = 27.5\text{kN/m}^2$$

Live load, P_L

D24 The assessment live load for a structure on the trunk road network is the nominal HB loading (45 units)⁷. This load is applied to the road surface, and dispersed through fill material in accordance with the rules provided in Chapter 3 of BD12/01. The HB wheel load is assumed to be uniformly distributed at 1.1N/mm² over a square or circular contact area between the tyre and pavement. Thus the maximum load of 112.5kN acts over an area of 0.32m square or diameter 0.36m. For ease of calculation most engineers assume a square wheel patch, and this is followed in the example below. The determination of the vertical pressure due to the HB vehicle is complicated by the

overlapping of the individual bulbs of pressure from adjacent wheels along an axle and also those from wheels on adjacent axles (the HB load comprises 2 bogies each with 2 axles). The wheels on an axle are spaced at 1.0m centres; the 2 axles forming a bogie are spaced 1.8m apart. Also the distance between adjacent bogies can be varied - the greatest loading on a buried structure will be given by a minimum spacing of 6.0m. These rules provide the following relations for determining the vertical live load at the crown of the structure. For depths of cover up to 0.68m there is no overlap of the dispersal zones; thus the load at the crown of the structure is due to a single wheel load and can be determined from:

$$P_L = \frac{112.5}{(0.32+h_t)^2}$$

For depths greater than 0.68m and up to a maximum of 1.48m, the load at the crown will be due to the overlapping dispersal zones from 4 wheels on one axle and can be determined from:

$$P_L = \frac{4 \times 112.5}{(0.32+h_t) \times (3.32+h_t)}$$

where 3.32m is the distance between the outer edges of the contact areas for the tyres at the ends of an axle.

For depths greater than 1.48m and up to a maximum of 5.68m, the load at the crown will be due to the overlapping dispersal zones from 8 wheels on one bogie and can be determined from:

$$P_L = \frac{8 \times 112.5}{(3.32+h_t) \times (2.12+h_t)}$$

where 2.12m is the distance between the outer edges of the contact areas for the tyres on adjacent axles.

For depths greater than 5.68m, the load at the crown will be due to the overlapping dispersal zones from all

⁷ The nominal vertical live loads specified in BD 12 are the HA single wheel load (100kN) and HB loading, which comprises an arrangement of 4 axles, each of which has 4 wheel loads. The arrangement of the HB vehicle is given in BD37 (DMRB 1.3). A unit of HB loading is equivalent to 10 kN per axle; thus the maximum of 45 units is equivalent to 45 tonnes per axle and 112.5kN per wheel. This provides a more onerous loading than the HA wheel load and thus the latter can be disregarded for the assessment of CSBS on the trunk road network. However it might need to be considered for other classes of road.

16 wheels of the vehicle and can be determined from:

$$P_L = \frac{16 \times 112.5}{(9.92 + h_t) \times (3.32 + h_t)}$$

where 9.92m is the distance between the outer edges of the contact areas for the tyres on adjacent bogies where the bogies are 6.0m apart.

In this example the crown of the structure is 1.0m below the surface of the road pavement and thus the live load pressure at the crown is:

$$P_L = \frac{4 \times 112.5}{(0.32 + 1.0) \times (3.32 + 1.0)} = 78.9 \text{ kN/m}^2$$

Hoop load, C_{ass}

$$\begin{aligned} \text{D25 } C_{\text{ass}} &= [S(P_d + P_L)]/2 \\ &= [3.0 \times (27.5 + 78.9)]/2 \\ C_{\text{ass}} &= 159.6 \text{ kN/m} \end{aligned}$$

Assessment hoop stress, $f_{a(\text{ass})}$

D26 In this example, the CSBS has a 152mm x 51mm corrugation and a nominal plate thickness of 3.5mm. The nominal area of section (a), obtained from Table A2b, is 4343mm²/m run. On inspection the worst wall thickness over a substantial length is found to be 3.15mm and thus the residual area of section (a_r) is calculated accordingly.

$$a_r = (3.15/3.5) \times 4343 = 3909 \text{ mm}^2/\text{m run}$$

Calculate assessment hoop stress

$$\begin{aligned} f_{a(\text{ass})} &= (C_{\text{ass}}/a_r) \times \gamma_{f3} \\ \text{where } C_{\text{ass}} &= 159.6 \text{ kN/m} \\ a_r &= 3909 \text{ mm}^2/\text{m} \\ \gamma_{f3} &= 1.15 \text{ (see Table 4.1 of BD 12/01)} \\ f_{a(\text{ass})} &= (159.6 \times 10^3/3909) \times 1.15 = 47 \text{ N/mm}^2 \end{aligned}$$

Yield strength

D27 The assessment hoop stress shall not exceed the minimum yield strength (f_y) of the steel divided by $\gamma_m = 1.3$. For assessment purposes, the minimum yield strength for most of the CSBS installed in the UK may

be taken as 230N/mm².

$$f_y/\gamma_m = 230/1.3 = 177 \text{ N/mm}^2$$

which is greater than 47N/mm² and therefore the structure satisfies the assessment check for yield strength.

Check seam strength

D28 On inspection the steel thickness at a seam is found to have reduced by 10% over a significant length. From Table A2b it can be seen that the nominal seam strength for this structure is 1232kN/m run.

Estimated residual seam strength

$$f_{s(\text{res})} = 1232 \times 0.9 = 1109 \text{ kN/m}$$

For a bolted segmental structure the assessment compressive hoop load (C_{ass}) x γ_{f3} (for the appropriate value of γ_{f3} see Table 4.1 of BD 12/01) shall not exceed the residual seam strength divided by $\gamma_m = 2.0$.

$$f_{s(\text{res})}/\gamma_m = 1109/2 = 554.5 \text{ kN/m}$$

which is greater than the assessment compressive hoop load ($C_{\text{ass}} \times \gamma_{f3} = 159.6 \times 1.15 = 183.5 \text{ kN/m}$) and therefore the structure satisfies the assessment criteria for the seam strength check.

Buckling check

D29 The assessment hoop stress shall not exceed the nominal buckling stress (f_c) divided by $\gamma_m = 1.3$. The nominal buckling strength should be determined in accordance with BD 12 but for assessment the cross-sectional area of corrugated steel per unit length (a) should be replaced by the residual area of section (a_r). Similarly, as discussed in D11, the effect on the value of I of any corrosion of the steel plate or change in shape of the corrugation should be taken into consideration.

Nominal buckling stress, f_c

$$f_c = \frac{f_y}{1 + \left(\frac{f_y}{f_b} \right)}$$

where $f_y =$ minimum yield stress of steel = 230N/mm²

$f_b =$ theoretical transverse elastic buckling stress. The method used to determine this stress is dependent upon both the depth of cover and the span of the structure (see Clause 5.10 of BD 12/01). In this example the span of the structure is greater than the depth of cover and thus the stress is determined from:

$$f_b = \frac{2}{a_r} \sqrt{\frac{k_e E I h}{(1-m^2) S}}$$

where: $a_r =$ residual area of section which, for this structure, is 3.909mm²/mm (see D26)

$E =$ Modulus of elasticity of steel = 205 x 10³N/mm²

$I =$ cross sectional moment of inertia per unit length. For a pristine structure of this type, a value of 1313mm⁴/mm is specified in Table A2b. In this example, inspection of the structure indicates that deformation of the structure and corrosion of the steel plate have reduced its value by approximately 10%, thus $I = 1313 \times 0.9 = 1182\text{mm}^4/\text{mm}$

$h =$ nominal depth of fill = 1.375m

$m =$ Poisson's ratio of steel = 0.3

$k_e =$ modified coefficient of soil reaction (N/mm³). The method used to determine k_e is dependent upon the shape of the structure (see Clause 5.10 of BD 12/01). For the circular structure used in this example, the value is determined from:

$$k_e = \left[1 - \left(\frac{r}{r+H} \right) \right] k$$

where $k =$ coefficient of soil reaction

$$k = \frac{0.333 M^*}{1000 r}$$

where $M^* =$ constrained soil modulus, as defined in Chapter 5 of BD 12/01. In this example the structure is installed through an embankment and the surrounding backfill has been found to have a dry density in excess of 90% of the maximum dry density. From Table 5.1 of BD 12/01, a (minimum) value of 33N/mm² can be assumed for M^* .

$$k = \frac{0.333 \times 33}{1000 \times 1.5} = 7.326 \times 10^{-3} \text{ N/mm}^3$$

$$k_e = \left[1 - \left(\frac{1.5}{1.5+1.375} \right)^2 \right] 7.326 \times 10^{-3} = 5.33 \times 10^{-3} \text{ N/mm}^3$$

$$f_b = \frac{2}{a_r} \sqrt{\frac{k_e E I h}{(1-m^2) S}} = \left(\frac{2}{3.909} \right) \sqrt{\frac{5.33 \times 10^{-3} \times 205 \times 10^3 \times 1182 \times 1.375}{(1-0.3^2) 3.0}} = 412.6 \text{ N/mm}^2$$

$$f_c = \frac{f_y}{1 + \left(\frac{f_y}{f_b} \right)} = \frac{230}{1 + \left(\frac{230}{412.6} \right)} = 147.7 \text{ N/mm}^2$$

The assessment hoop stress shall not exceed the nominal buckling stress (f_c) divided by $\gamma_m = 1.3$.

$$f_{a(\text{ass})} = 47\text{N/mm}^2$$

$$f_c/1.3 = 147.7/1.3 = 113.6\text{N/mm}^2$$

thus the structure satisfies the assessment criteria for buckling.

APPENDIX E DETERIORATION OF IN-SERVICE CSBS

E1 This Appendix covers the common types of deterioration seen in CSBS in the UK and describes methods of refurbishing deteriorated structures. It also provides some examples of structures exhibiting typical forms of deterioration and guidance on suitable methods of refurbishment and preventative maintenance.

INVERT SCOUR

E2 Scour can lead to extensive deterioration of the invert of a culvert. It usually occurs in culverts that do not have a paving and are subject to flows of water where the velocity is sufficient to carry sand, gravel and stones through them. The scouring action of the water-borne debris removes the protective coatings to the steel substrate. The rate of corrosion of the exposed steel may be rapid.

Figure E1 shows the deterioration in the invert of a 1.8m diameter CSBS acting as a culvert: this structure was subsequently replaced with a larger diameter helically wound corrugated steel pipe incorporating a reinforced concrete paving. If the deterioration had been less severe it might have been possible to install a reinforced concrete structural paving.

E3 It is important that invert pavings in structures subject to scour are maintained in good condition and that they are of sufficient extent to contain the stream during peak flow conditions. Note that in larger span structures (particularly circular pipes) the invert may be buried under a natural stream bed, and thus is difficult to inspect. Peak water flows may scour this natural bed causing deterioration to the buried surfaces, and this might not be seen during a superficial inspection.

E4 Helically wound and riveted pipes may have been provided with a bitumen invert paving during manufacture, but in situ reinforced or mass concrete pavings have also been provided to such structures. If the loss in metal in the invert is not excessive and the structure does not require strengthening, an invert paving, as detailed in BD 12, may be installed. Should, however, the loss in metal be significant and the structure fails an assessment then, providing the upper portion is sound, a structural paving may be installed. This is perhaps most easily done through the placement

of a reinforced concrete paving to BD 12. A good shear connection between CSBS and paving is required and the paving must be of sufficient strength to restore the ring stiffness of the structure. Note that bitumen does not provide a good shear connection and it may be necessary to install shear connectors to promote adequate adhesion of the paving to the CSBS invert. In such cases, as welding of the shear connectors will melt or remove the hot dip galvanise treatment, the metal surface coating should be reinstated afterwards, using either zinc rich paint or cold galvanising.

E5 Even if the structure passes its assessment it may still be more economical to provide a structural concrete invert paving where it is difficult to achieve the required refurbishment (i.e. adequate corrosion protection) for a non-structural solution. Alternatively, catch pits, drop inlets and the like might be placed at the upstream end of a structure, but these must be regularly maintained to ensure their proper operation and prevent blockage of the water channel.

E6 A procedure for installing a non-structural reinforced concrete invert paving is as follows:

- (i) Refurbish the surface of the steel plates to the 'Clean Steel' or 'Sa2' classification given in Clause 5004 of the SHW by blast cleaning.
- (ii) Coat the steel plates with cold-applied bitumen.
- (iii) Place the reinforced concrete paving to the requirements of BD 12.
- (iv) Shape the top edge of paving to prevent ponding of water against the wall of the CSBS.
- (v) Seal the top edge of invert paving by coating the interface between the steel plates and concrete paving with a cold-applied bitumen paint.

OVERTOPPING OF THE INVERT PAVING

E7 A common problem is that the invert paving is not high enough to protect the structural plates. Causes of this problem include:

- (i) turbulent flow due to the poor alignment of the culvert with the existing watercourse; and
- (ii) a reduction in invert paving level due to differential settlement along the line of the CSBS.

Deterioration may arise (a) through scour by the action of debris carried by the water and (b) by frequent wetting and drying.

Figure E2a shows typical deterioration of a bitumen coating caused by frequent cycles of wetting and drying. Figure E2b shows the deterioration of the coatings above the paving in a pipe arch structure due to overtopping through turbulent flow: note that the bitumen coating was in good condition elsewhere in the structure. A poor alignment might arise from the desire to keep the length of the structure to a minimum.

E8 The most straightforward maintenance measure, assuming the deterioration of the steel is not excessive, is to increase the height of the invert paving on sides. The following procedure should be followed:

- (i) Remove any loose secondary coating and corrosion products.
- (ii) Refurbish the galvanised steel or exposed steel surface as appropriate (the standard of surface preparation should be compatible with the protective coating to be applied).
- (iii) Apply an additional compatible protective coating. For most structures, it would be appropriate to protect bare steel with a cold-applied zinc rich paint followed by a cold-applied bitumen-based product.
- (iv) Alternatively, for a hot dip galvanise structure, its surface should be cleaned in accordance with MCHW Clause 5005 and followed by applying a compatible primer or an adhesion promoter and finally by epoxy paint.
- (iv) Protect the inner surface of the culvert by providing a concrete lining on the sides to at least the level of the mean winter flow plus 200mm, or greater if necessary to contain turbulent flow.
- (v) Seal the joint between the top of the raised part of the concrete lining and the wall of the CSBS by coating the interface with a cold-applied bitumen or coal tar free pitch epoxy product (HA item 150 or High build epoxy hydrocarbon resin modified (HA item 151).

Figure E3 shows, the details of raising the sides of paving within a pipe arch structure that was constructed with a flat reinforced concrete paving.

DETERIORATION OF BITUMEN PAVING

E9 Bitumen pavings are generally hard wearing and resistant to scour by water-borne debris. The most common form of deterioration of bitumen pavings takes the form of cracking as the bitumen hardens with age and loses its more volatile constituents. This is usually most evident at the ends of the structure (particularly those with bevelled ends) exposed to direct sunlight and potentially turbulent water flows. Figure E4 shows an example of the form of deterioration.

E10 Where the steel in the invert has deteriorated substantially the use of a structural reinforced concrete paving should be considered rather than the replacement of the structure. If the deterioration of the structure is slight then the paving should be replaced or repaired. There are a number of ways to repair a damaged bitumen paving including replacing the damaged areas with one of the following:

- (i) Hot-applied bitumen trowelled into place.
- (ii) Cold-applied bitumen-based product, such as cold-rolled asphalt.
- (iii) Reinforced concrete.

Alternatively, pre-coated galvanised steel or pre-shaped glass reinforced plastic sheets could be fixed into the invert as a liner and the resulting void between the liner and CSBS filled with a cementitious grout or water-reactive polyurethane foam - details are shown in Figure E5.

E11 The preliminary steps to be taken in the repair of bitumen pavings are as follows:

- (i) Divert the water flow and dry the invert.
- (ii) Remove all loose bitumen paving and clean the exposed surface of the CSBS.
- (iii) Coat the galvanised surface or exposed steel with a cold-applied bitumen-based paint.
- (iv) Repair or replace the paving or fix liner sheets.

E12 The use of liner plates might be a particularly effective method of paving repair because:

- (i) The use of reinforced concrete to repair a short length of damaged bitumen paving may be problematic as bitumen pavings placed to the AASHTO M190 Standard are only required to be 3mm above the crest of the corrugations of the CSBS whereas reinforced concrete pavings placed to the requirements of BD 12 need to be at least 100mm above the crest. This difference will result in an obstruction in the water channel and may cause turbulent flow inside the structure. It may be preferable to replace the whole of the bitumen paving with a reinforced concrete paving where a significant length of the original bitumen paving is damaged, as long as the hydraulic capacity of the structure is not impaired by the increased height of the paving.
- (ii) Few repairs have been made to bitumen pavings with hot-applied bitumen or asphalt-based products. Thus the ease of application and the durability of the repair are, largely, untried.

The manufacturers of CSBS may be able to supply pre-shaped steel liner plates, but uncurved thin sheets of coated steel may be laid and pulled into the correct curvature using the circumferential fittings fixed to the CSBS. Adjacent sheets would need to be joined with bolts or rivets. Glass reinforced plastic liners need to be pre-shaped to the profile of the culvert and joined along the length of the culvert.

DETERIORATION ALONG THE WET/DRY LINE

E13 CSBS acting as culverts are susceptible to deterioration along the wet/dry line. This is often most pronounced in structures with standing water, or with little or no flow, where the secondary coating has been removed in the wet/dry zone and yet remains in perfect condition either side of this zone. Secondary coatings formed from hot-dip bitumen to the AASHTO M190 Standard seem particularly susceptible, and are often completely removed within the wet/dry zone. Removal of the secondary coating leads to deterioration of the zinc coating and hence to corrosion of the underlying steel. This mechanism may result in a narrow band of corrosion running along the whole length of a structure.

E14 A coating may be reapplied to the wet/dry zone but this is likely to be quickly removed and again expose the underlying zinc coating and steel to the environment. The placement of a paving to contain the flow would protect the wet/dry zone, but there are a number of cheaper options. For example, the use of pre-coated galvanised steel or glass reinforced plastic sheets

as shown in Figure E6. This could be done in the following manner:

- (i) Remove any loose secondary coatings and clean exposed surface.
- (ii) Coat the galvanised surface or exposed steel with a cold-applied bitumen-based paint or suitable secondary coating.
- (iii) Secure the pre-coated galvanised steel or GRP sheets to the culvert walls to cover at least the wet/dry zone up to the height of the mean winter water level plus 200mm.
- (iv) Fill the void between the wall of the CSBS and the sheet with, for example, a cementitious grout or water-reactive polyurethane.

DETERIORATION DUE TO SEEPAGE

E15 Bolted segmental structures are particularly prone to seepage of water from the backfill into the structure either through the bolt holes or through the joints where the plates overlap. Few, if any, structures in the UK have been constructed with joint seals but secondary protective coatings such as bitumen may reduce seepage. The water may originate from the overlying carriageway, roadside verge or from ground water flowing through the backfill. De-icing salts or leachates may be carried into the structure and these may cause rapid deterioration around the points of entry. The degree of corrosion may depend, to some extent, upon the source of the seepage. Where water laden with de-icing salts percolates down from the surface, the corrosion may be limited to areas of the CSBS immediately below the carriageway edge or central reserve on a divided carriageway.

Figure E7 shows the interior of a 35-year old plain galvanised bolted segmental CSBS where deterioration is particularly severe below the edges of the carriageways. Excavation and exposure of the outside of the structure at this point showed that the exterior had suffered no corrosion. Indeed on the soil side the thickness of the remaining zinc was about 60% of its nominal original thickness despite the fact that no external secondary coat had been used.

Figure E8 shows the deterioration in a 25-year old plain galvanised arch structure. Again water laden with de-icing salts has percolated into the structure below the edges of the carriageway. Corrosion is most noticeable around bolt holes and plate edges in the

crown and also where it has ponded in the seating channel of the arch. The rest of the structure is in good condition.

The maintenance to the structures shown in Figures E7 and E8 would be similar:

- (i) Grout the backfill close to points of seepage with a water-reactive polyurethane grout or similar to eliminate or reduce seepage.
- (ii) Remove corrosion by sand or shot blasting to achieve a clean steel finish.
- (iii) If the appearance of the structure is important, i.e. an underpass, then a visually attractive finish could be applied to the structure by applying an appropriate primer and coating system, for example, a zinc phosphate primer followed by a high-build primer and an acrylic finishing coat.
- (iv) If the appearance of the structure is unimportant, then the finish to the structure could be formed from a moisture-tolerant primer followed by a coal tar epoxy or cold-applied bitumen coating.
- (v) If the deterioration is severe but localised then liner plates could be used to strengthen the structure. Figure E9 shows the use of liner plates in an underpass.

STRUCTURAL INSTABILITY OF THE INVERT

E16 Structural instability of the invert can arise in a number of ways, but for ageing structures it would probably be due to excessive material degradation. As noted in E10, where the invert is badly corroded it might be feasible to increase the structural capacity of a CSBS through the placement of a structural paving.

E17 Details of various arrangements for structural pavings are provided in Figures E10a to f.



Figure E1 Example of extreme corrosion in the invert of a structure subject to scour
(this 30 year old structure was not provided with a paving or bitumen coating)



Figure E2a Deterioration along the wet/dry line in low flow conditions



Figure E2b Damaged caused by overtopping of paving during turbulent flow

Figure E2 Damage to bitumen coatings by low and turbulent flows

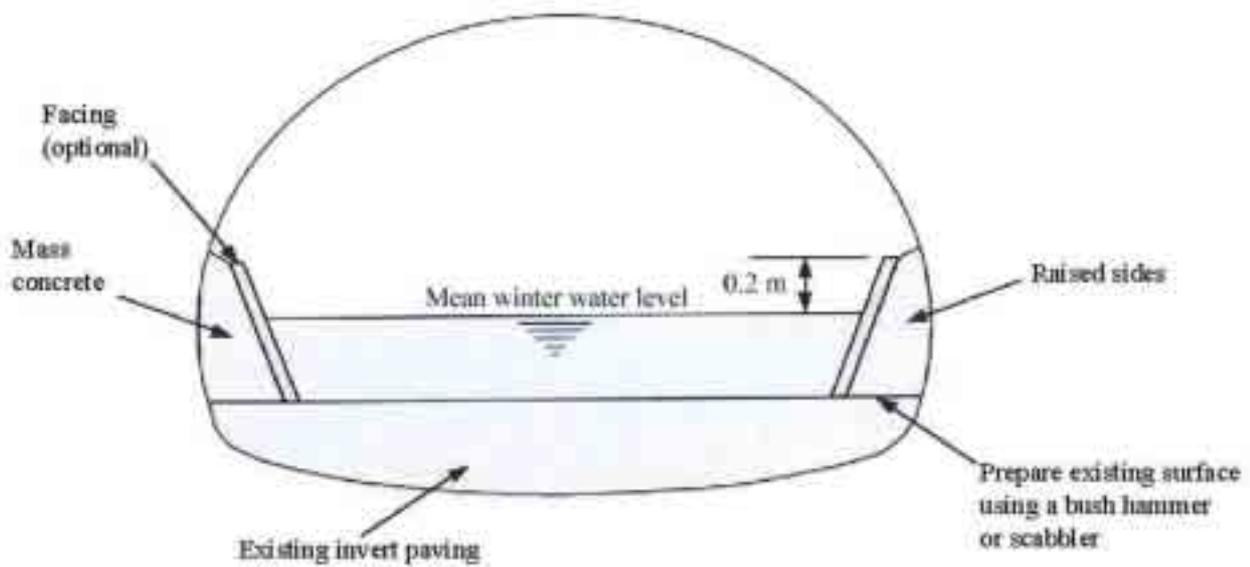


Figure E3 Extension of an invert paving



Figure E4 Cracking in a bitumen paving due to exposure to sunlight

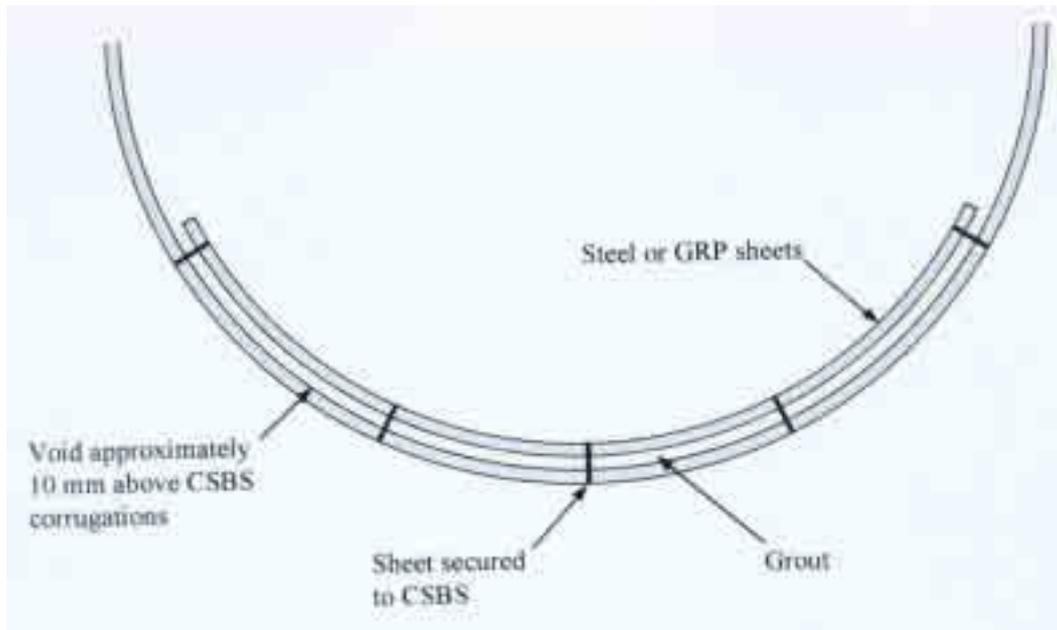


Figure E5 Use of liner plates to protect an invert

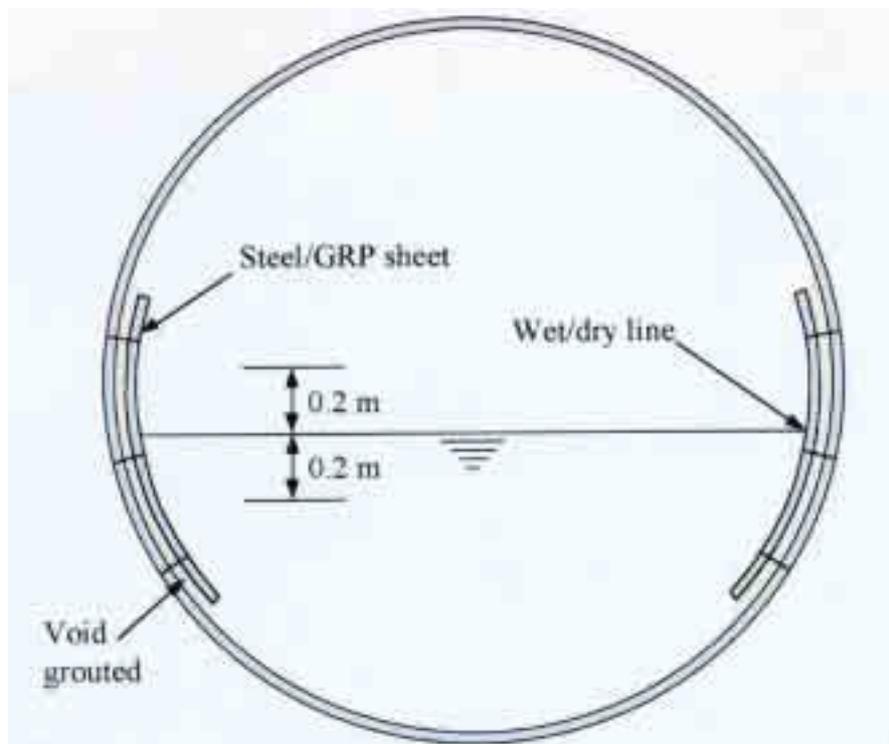


Figure E6 Use of liner plates to protect wet/dry line



Figure E7 Deterioration to side plates in a plain galvanised bolted segmental CSBS caused by seepage below the edge of the carriageway



Figure E8 Deterioration at the arch seating of a plain galvanised arch structure due to seepage and ponding of water containing de-icing salts



Figure E9 Use of liner plates to repair a bolted segmental CSBS showing deterioration below the edge of the carriageway due to seepage of water containing de-icing salts

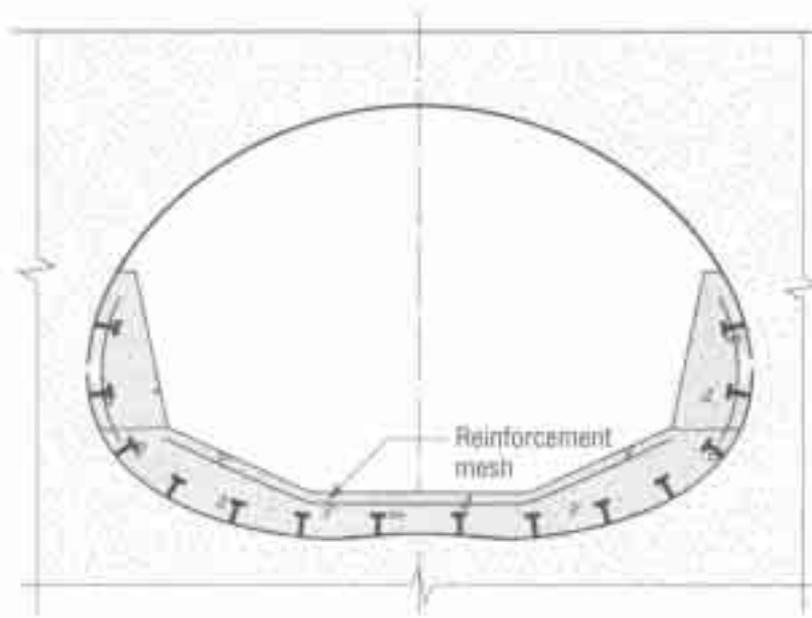


Figure E10a Reinforced concrete paving (after Abdel-Sayed et al, 1993)

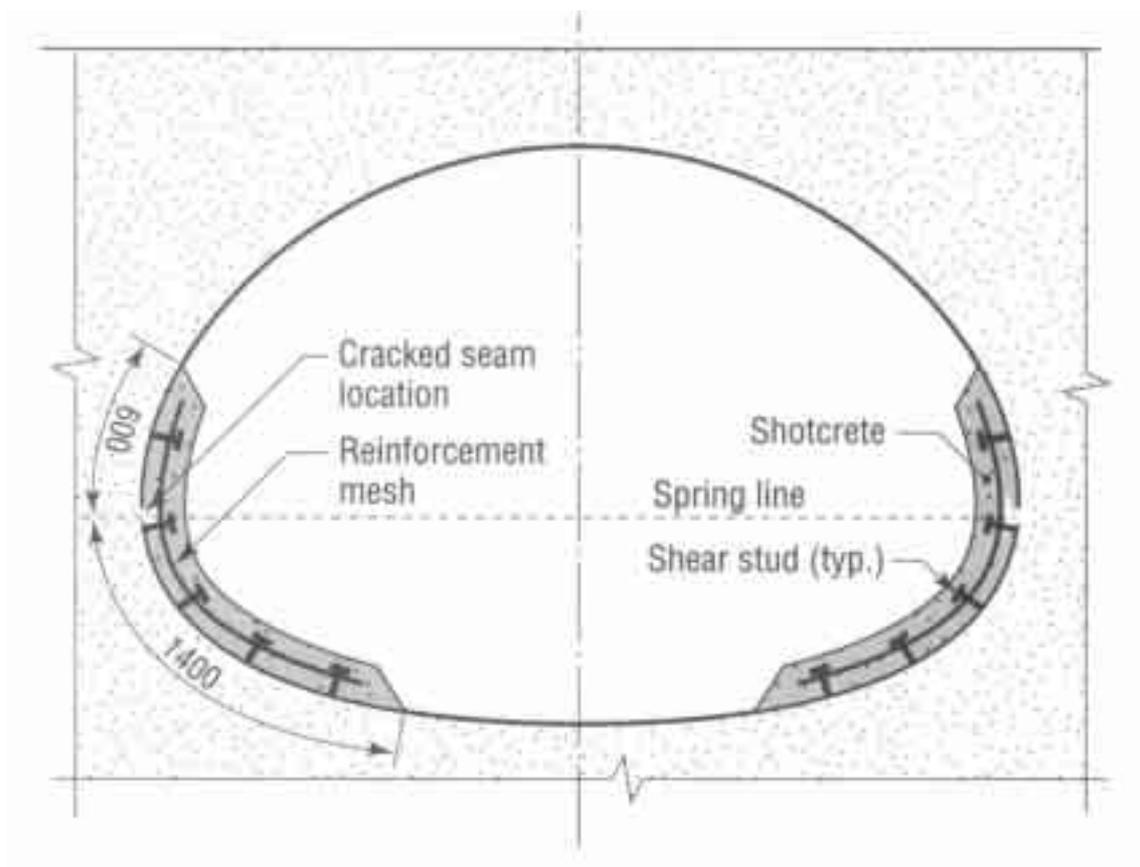


Figure E10b Shotcrete reinforced concrete paving (after Abdel-Sayed et al, 1993)

Figure E10 Details of structural concrete pavings for repairing the invert of CSBS (part 1 of 3)

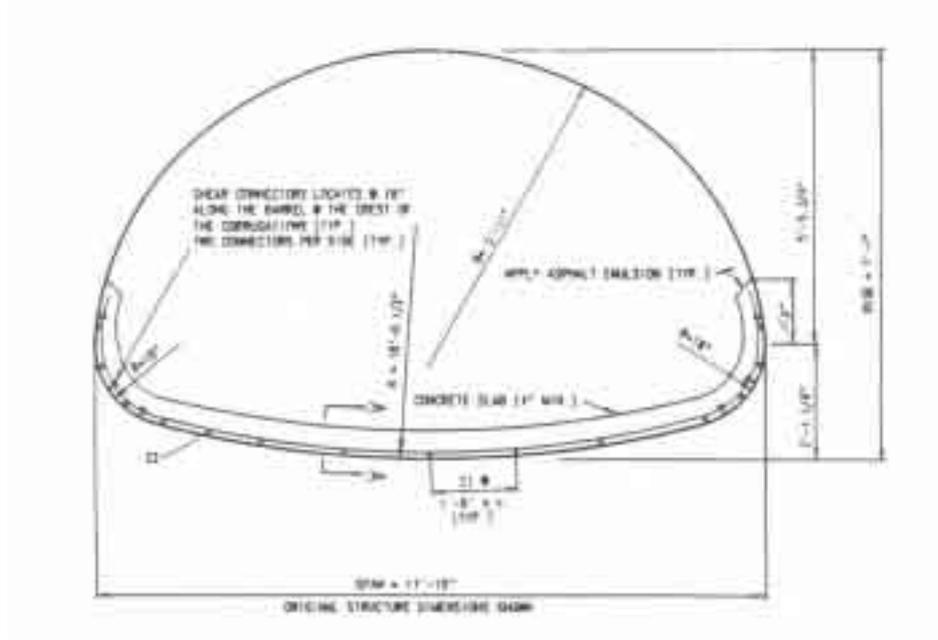


Figure E10c Reinforced concrete paving in a multi-plate pipe-arch as used in Maine (after Alexander et al, 1994)

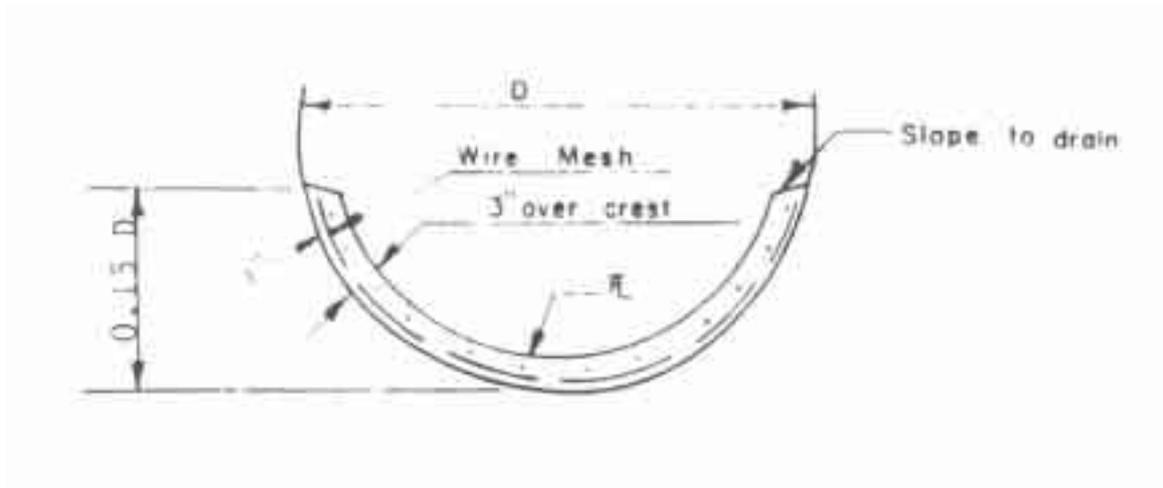


Figure E10d Reinforced concrete paving in a circular pipe as used in Ohio (after Alexander et al, 1994)

Figure E10 Details of structural concrete pavings for repairing the invert of CSBS (part 2 of 3)

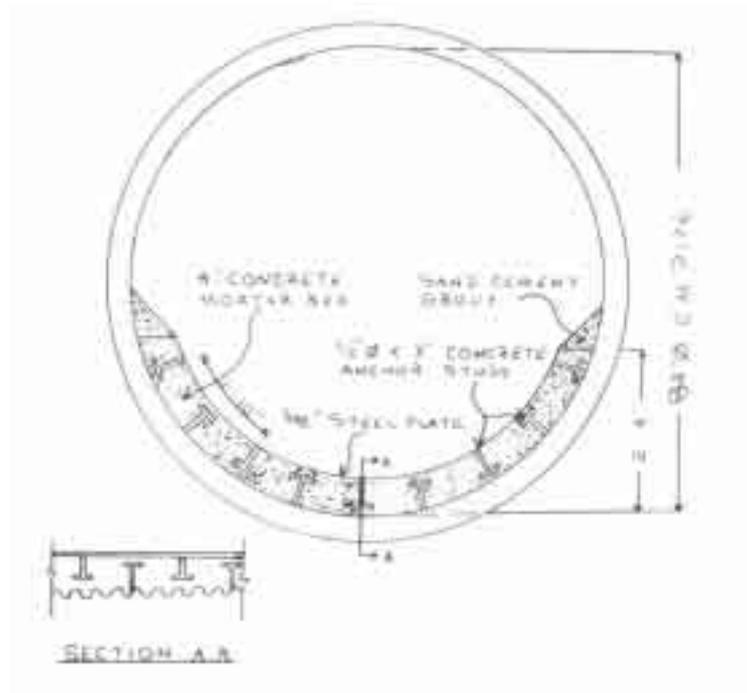


Figure E10e Paving formed from a steel plate and mass concrete as used in Alabama (after Ikerd, 1984)

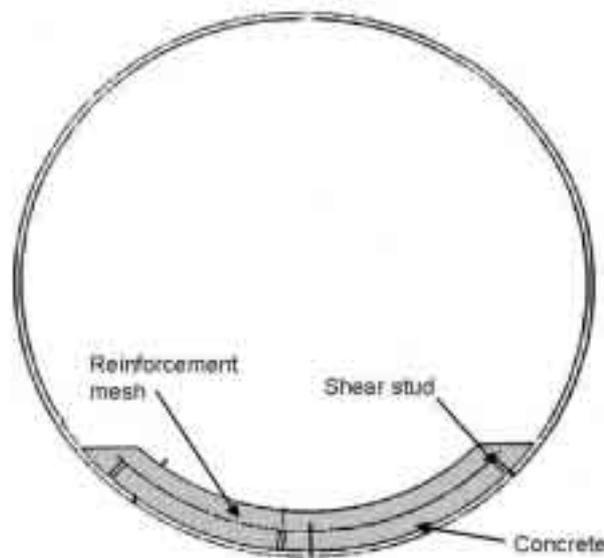


Figure E10f Reinforced concrete paving as used in Hawaii (after Alexander et al, 1994)

Figure E10 Details of structural concrete pavings for repairing the invert of CSBS (part 3 of 3)