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The Pathology of Metal Culverts

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The Pathology of Metal Culverts

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SYNOPSIS Metal culverts are robust structures, but the very large number built every year entails, statistically, a rather high level of pathology. The various aspects of this pathology are analyzed below, first from a general point of view and then through an examination of three particularly instructive cases.

INTRODUCTION

In September 1981, the French authorities published a complete collection of Recommendations covering the design, engineering, and construction of metal culverts (1). These spécifications were issued in part because of the relatively large number of pathological cases, and in particular because of a rash of problems during the construction of the larger works.

It should be pointed out that, before the publication of these specifications, each supplier assumed responsability for the engineering of his works during the implementation stage, and this, because of competitive pressures, had led to some excesses.

The writing of this document was an excellent opportunity to count and classify the various types of pathology that can affect these structures. One of the main conclusions to be drawn from this study is that in almost all cases the pathology of the metal culverts is caused by defective design or workmanship, often because of a transgression of design or engineering rules.

It should nevertheless be pointed out that the disorders found most often result from a combination of several causes, and that it would be hazardous to ascribe them too hastily to any single cause without a complete investigation.

In this paper, we shall first describe the various type of incident that have been found; we shall then illustrate, using three concrete examples, how the causes of pathology can combine to result in the partial or total ruin of a structure.

THE VARIOUS ASPECTS OF PATHOLOGY

In approaching the study of the pathology of metal culverts, we must distinguish between two fundamentally different stages in the life of the structure :

- The construction stage, during which the wall of the structure is subjected to bending forces resulting from the gradual building up of the embankments on the sides and from their compaction. During this stage, the structure will tend to undergo deformations affecting its cross-section.

- The stage build-up of the covering enbankments and the service stage, during which the wall will be loaded primarily in compression. At this point, any deformation of the structure, totally confined by the embankment, can only result from a deformation of the subsoil or the embankments themselves.

1) Pathology during construction

It is rather common for disorders to appear during this stage. Thus, most of the cases of ruin through the sudden collapse of the culvert or of a portion of it that have occurred in France in recent years have occurred before the covering embankments were built. The main causes of these incidents are :

- the inadequacy of the inertia of the wall of the structure with respect to its dimensions;

- excessive forces introduced by the active pressure of the embankments, either because the materials were of poor quality or because they were not placed with sufficient care;

- poor timing of the filling operation tending to introduce asymmetrical forces that are very hard for the structure to withstand.

The most commonly encountered case is that of "pear-shaped" déformation of the ends of the structure. When they are cut slantwise, they are very flexible because of the highly marked anisotropy of the corrugated sheet metal. This is why, in the absence of stiffeners, deformation of the ends is practically inevitable as soon as the structure reaches a certain size. This effect is frequently aggravated by an excessive skewing of the structure, wich substantially increases the cut length of the free end. In many cases, this defect results in an ugly deformation of the end of the structure (figure 1), but in extreme cases the earth pressure is sufficient to reverse the curvature of the first few sheets, causing the end to collapse. We shall see, in case no. 1 described below, an especially instructive example of this type of failure.

FIGURE 1

In certain relatively rare cases, when the wall of the structure has been under-engineered (inertia too low), there may result a type of deformation that is similar but extends to the whole body of the structure (figure 2); the pressure of the embankment, maximum in the transition zone between the haunches and the crown, may here again be sufficient to reverse the curvature of the corresponding plates. The structure is then quite unfit for normal use, and it would be extremely dangerous to continue filling, since this would most likely lead to collapse.

FIGURE 2

In the case of very large structures, the pear shape becomes unstable well before the functional filling is completed, and in one case the result was a complete "cloverleaf" collapse; fortunately, there were no victims (figure 3).

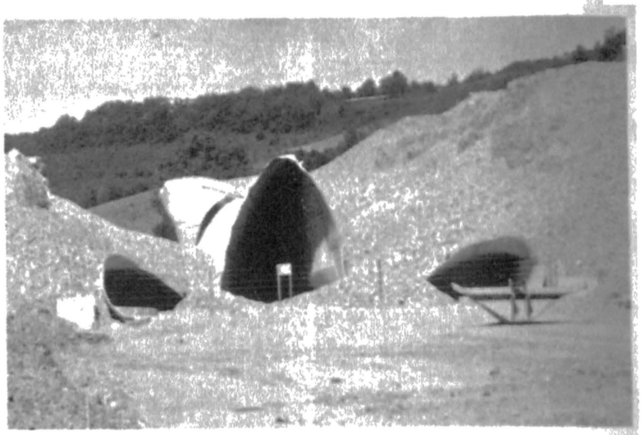

FIGURE 3

It may also happen, either because of poor staging of the filling work or because of imprope design of the covering fill, that the structur is subjected to asymmetrical forces. Given the flexibility of the wall, the section is deformed and yields until a new equilibrium is reached.

Such deformations generally have no effect on safety of the structure, but we have witnessed one extreme case in which the lateral yielding continued to collapse of the culvert (figure 4 Care should also be taken not to introduce suc asymmetrical forces into a structure already built (as by digging a trench near it).

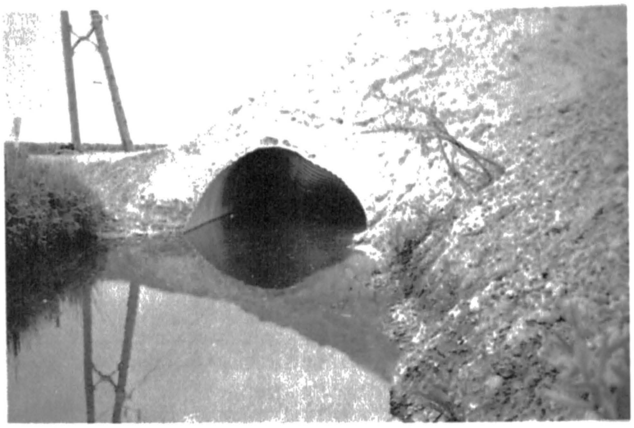

FIGURE 4

2) Long-term deformations

In contrast to the cases mentioned above, in which deformations result systematically from excessive forces introduced into the structur long-term deformations always arise because o the poor quality of the soils or fill surroun the culvert, which are deformed at constant s (subsidence, creep) and in turn deform the st ture.

The commonest type of deformation in this cla is a loss of the original longitudinal profil because of subsidence of the subsoil.

In most cases, the differential subsidence results from the variation in the fill load, nil at the ends of the work and maximum at its centre; this creates a low point at the centre of the structure, where stagnant water can accumulate and aggravate corrosion. The remedy is to anticipate the amplitude of this subsidence with sufficent accuracy and build the structure with the reverse deformation so that the ultimate profile will be straight.

Less often, differential subsidence may be caused by a heterogeneity of the subsoil, such as the presence of faults bounding a strong stratum and a soft stratum. In extreme cases, the deformation may be such as to result in shearing of the culvert (figure 5). For this reason, there should be a sufficiently dense geotechnical survey along the centreline of the structure.

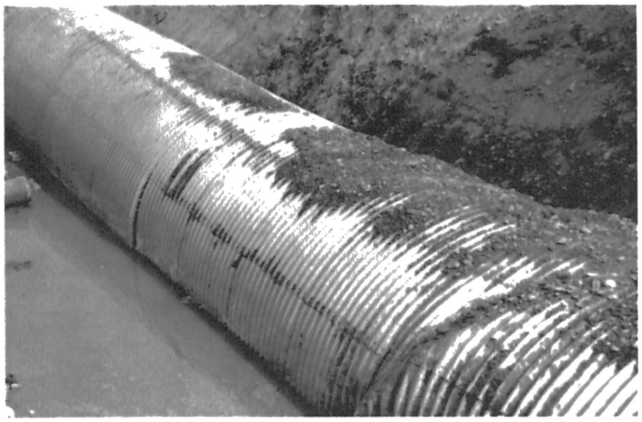

FIGURE 5

Delayed deformations of the cross section are also encountered. There are two main types :

- The sinking of the corner plates of "arch culverts";which have floors made of plates with a large radius of curvature joined to the crown plates by parts having a small radius of curvature. If the subsoil is mediocre and has not been removed and replaced by a sufficient thickness of a properly compacted soil having better properties, there is a risk that the corner plates, which exert a strong pressure on the soil, will be driven into it, causing in extreme cases a reversal of the curvature of the floor plates (figure 6). In benign cases, this effect, which remains limited, may be caused by inadequate compaction of the funtional fill under the corner plates, a fill that is very hard to place because of the difficulty of access.

- Transverse flattening of the culvert, which is very rare, generally results from a rather gross error in the assessment of the mechanical properties of the adjacent fill. It is caused by a lateral creep of the fill under the influence of the thrust, resulting in a lowering of the crown that may go as far as the collapse of the culvert. This phenomenon was observed in one structure built in a cutting, in soils of very poor quality, and in another for which the functionnal fill used was much too clayey.

3) Denting, perforations, and local damage

These are generally local problems that may occur either during the building of the structure, in which case repairs are in general easy, or after commissioning, which makes repairs much more delicate.

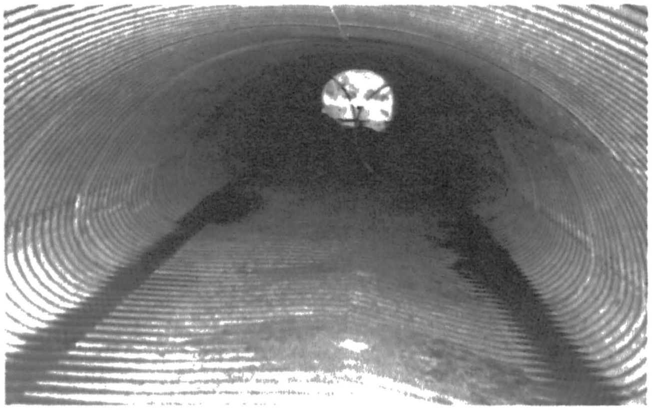

FIGURE 6

In the first category, we rather often find deformations caused by :

- dumping of earth too close to the wall;
- impacts by levelling machines;
- contacts between compactor rolls and the walls of the culvert, which may also result in the shearing of some of the bolts;
- travel on the structure by various machines when it is still inadequately covered, or not at all.

The second category includes :

- impacts by floating objects with the inadequately protected ends of the culverts;
- dents (or more often "scrapes") caused by vehicles travelling inside the structure, if it is too small for them or there are no guides (pavements, barriers).

4) Abrasion and scouring

We shall mention only for the record the well-known phenomena of abrasion to which metal culverts are subjected by waters containing particulate matter. The only viable way of forestalling it is to protect the bottom of the culvert with a hard-wearing floor of bituminous concrete, which must be resurfaced from time to time.

As for the phenomena of scouring, on the other hand, a peculiarity of behaviour resulting from the very light weight of the culvert and the flexibility of the slant-cut end is worth noting : the ends of hydraulic works are generally subjected to uplift, and the greater the velocity of the water flow in the structure and the larger the loss of head at the inlet, the larger the difference beween the uplift and the water pressure on the inside of the wall.

As soon as they have begun, these deformations tend to be quickly accentuated by the hydrodynamic action of the current. The damage that has been observed in such cases is sometimes spectacular, as will be seen partially in case no. 3 below. The way to protect against this phenomenon is not only to build the usual cut-off walls, but also to anchor the ends of the culvert firmly to them so that their weight prevents any lifting.

5) Corrosion

This phenomenon, familiar in underground metallic structures, will be mentioned only for the record. We point out, however, that the Recommendations cited in the introduction attempt to limit it by restricting the use of such structures to little or moderately corrosive environments and by laying down criteria for the selection of fill materials aimed at holding corrosion of the underground side of the structure to a minimum. In this connection, we can cite the case of a culvert 3 mm thick perforated in 18 months by a corrosive functional fill.

CASES STUDIES

STRUCTURE No. 1

This is an arch culvert 5.25 mm thick having a span of about 9.20 m and a rise of 5 m. It is highly flattened (V/D = 0.54) and highly skewed (65 gr) (figure 7).

The total length of complete rings (15 m) is comparable to the total length of the truncated chamfered slant-cut ends (2 x 7 m).

The stream was diverted to the left bank to allow for the construction of cut-off walls at both ends, and of the base and of small functional embankments made of a very good material. Stone riprap was use to protect the embankments.

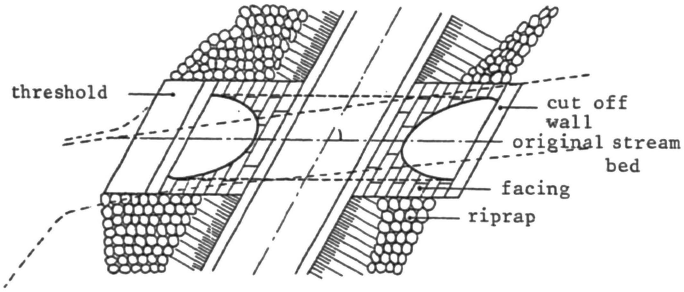

FIGURE 7

1) Disorders found

Failure occured on the night following the completion of the filling work (the stream was then running in the culvert), during a rising of the waters caused by heavy rainfall, although the waterway did not reach a critical level (in fact, another culvert of half the span already built on the same stream did not suffer any damage). The culvert was found broken up in the stream bed, shifted bodily, and almost all of the fill surrounding it had been carried off by the water (figure 8).

2) Causes of the disorders

The failure of the structure seems to have been caused by a number of factors working together. Mention should be made of the asymmetrical loading of the upstream end of the structure on the side projecting towards the bed of the waterway, caused by the greater height of the embankment and accentuated by the presence of a bulldozer in that zone.

FIGURE 8

The most plausible explanation assumes that the water acted preferentially on the projecting end of the culvert, which was protected by some riprap but not yet anchored in the cut-off walls. This end, highly deformable and overloaded by the asymmetry of the embankment and the presence of the bulldozer, probably then collapsed, taking with it the rest of the structure which was, too short for a state of equilibrium to reached by a partial collapse. Once the bed of the stream was obstructed, one can readily imagine that erosion on either side of the culvert was very rapid.

3) Measures taken and repairs made

The culvert was completely rebuilt; naturally, changes were made to make the construction saf

- the skew was reduced to 67,30 degrees;
- the crown plates were "cap" cut at the ends provide stiffening during the construction sta
- the ends were given a truncated chamfer slan cut;
- the ends of the culvert were anchored along their entire perimeter in the cut-off walls and stone facings, built as the embankments were raised.

4) Lessons to be drawn and miscellaneous remai

Here we can lay stress on the conjuction of unfavourable circumstances (short structure, ge skew, asymmetrical loads, etc..), but the important lesson is that it is essential to protect against the danger of flooding during construction (if the waterway to be crossed i subject to sudden changes of level) by anchor the ends of the culvert before opening it to water, and by protecting the embankments as t are built.

STRUCTURE No. 2

This is an arch culvert having a span of abou 9 m and a rise of 6.50 m, made of galvanized steel 6.2 mm thick. It has a rather modest sk at one end (100 deg) and a very pronounced skew for this type of structure at the other end (123 deg) (figure 9).

1) Disorders found

When the culvert was in an intermediate stage of construction (about 1 m above the crown), th more skewed end collapsed over a subtantial le about a quarter of the total length of the stru

FIGURE 9

The asymmetrical collapse started from the projecting side of the end and propagated along the structure, ceasing only when the crown plates at the end were bearing against the floor (figure 10).

Field investigations were conducted to obtain further details of use in reaching an informed judgment. These included a topographical survey that revealed an asymmetrical transverse deformation of the entire structure, probably caused by an embankment that was itself asymmetrical; however, the transverse slope (approximately 20 %) of the covering embankment may also have been partially responsible for this deformation.

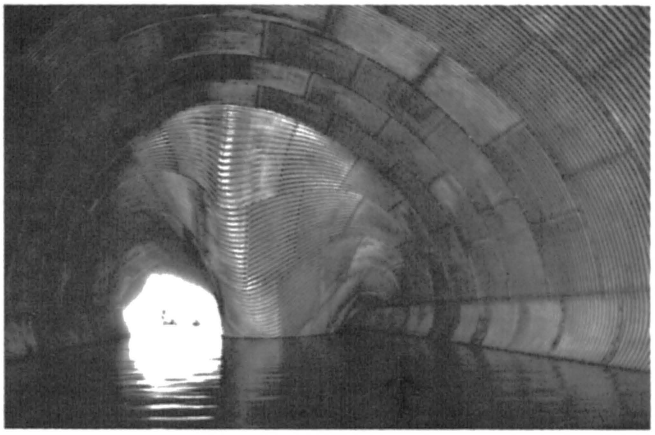

FIGURE 10

2) Causes of the disorders

The asymmetry of the height of the embankment is not by itself sufficient to explain the failure of equilibrium, since most of the structure stood up normally. It would seem that most of the blame must be assigned to the excessive skew and inadequate stiffening of the end that collapsed.

The portion projecting farthest, not benefitting from any vault effect, yielded to the thrust of the earth, causing the partial collapse of the culvert.

3) Measures taken and repairs made

After the culvert had been cleared along about half its length, the end of the structure was rebuilt; the unusable plates were replaced and the changes necessary to assure the stability of the structure were made.

It was decided :

- to reduce to a minimum the portion of the hyghly skewed end not consisting of complete rings and not benefitting from the vault effect by allowing a large share of the crown plates to project to form a "cap";
- to reinforce both ends with reinforced-concrete facings serving as stiffeners.

STRUCTURE No.3

This is a hydraulic structure near the sea consisting of two identical arch culverts having a span of about 8 m and a rise of 5,6 meters apart. The plates are 6.2 mm thick. This is a straight structure, the waterway having been improved accordingly.

Given the poor properties of the subsoil, it was replaced to a depth of about 1 m by quarry materials. Embankment stabilization banks were planned, suggesting a special cut for the ends of the culverts (highly elongated lips).

The total length of each culvert is 51 m, 34 m of it in the central portion, and the crowns are covered with 1.50 m of fill. The embankments are rendered impervious by a clay mask protected by riprap.

1) Disorders found

During a spring tide, at a time when the structure was embanked but the riprap not yet in place, the embankments were partially eroded around the culverts and the latter suffered serious deformation, essentially in the form of a reversal of the curvature of the floor (figure 11). No subsidence of the subsoil was observed.

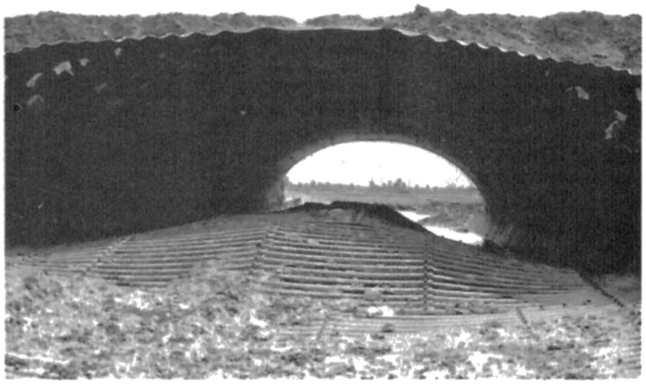

FIGURE 11

2) Causes of the disorders

It is difficult to establish the mechanisms of this incident, which occured over a weekend with no eye witnesses present. It probably involves a conjunction of unfavourable circumstances. It was agreed when the matter was settled that the inadequate quality of the fills used was the primary cause.

Indeed, not only were the clay masks much deeper than planned, creating a zone of very poor functionnal embankment around the ends of the culverts, but also the fill between the culverts (sand that had simply been sprinkled) was certainly not sufficiently compact. This explains why transverse deformations of the culverts could occur near the ends.

3) Measures taken and repairs made

The culverts were rebuilt, after clearing and the recuperation of the usable portions, with the following changes made :

- the use of more rigid truncated ends, anchored in cut-off walls;
- the building of stabilizing banks and riprap protection as the embankments were built up;
- making the embankment impervious by means of a sheet of polyurethane lined with Bidim nonwoven fabric, protected from the riprap by a layer of sand;
- new functional embankments made of 0/80 continuously graded quarry aggregate properly compacted by mechanical equipment on each side of the culverts;
- protection of the embankment around the culverts by the construction of a reinforced-concrete facing covered with quarry stones, cast on the embankment and with its base resting on the cut-off walls;
- the anchoring of the culverts to this facing by tie-backs.

4) Lessons to be drawn and miscellaneous remarks

As we have just seen, it is worth stressing the necessity :

- of producing functional embankments capable of performing their mechanical role of preventing deformation of the culverts, by using materials of adequate quality, compacted by the proper equipment;
- of protecting the structure from the action of the water during construction, if there is a risk of a sudden rise in the water level.

REFERENCES

(1) "Les buses Métalliques". Recommendations and rules of the art. SETRA-LCPC, Ministry of Transport, September 1981.