Collapse of corrugated metal culvert in Northern Sardinia: analysis and numerical simulations

Linda Giresini*, Mario L. Puppio and Mauro Sassu

DESTEC – Department of Energy, Systems, Territory and Constructions Engineering,
University of Pisa,
Largo L. Lazzarino 1, 56127 Pisa, Italy
Email: linda.giresini@unipi.it
Email: mariolucio.puppio@ing.unipi.it
Email: m.sassu@unipi.it
*Corresponding author

Abstract: The paper illustrates the possible causes of collapse of a Corrugated Metal Culvert (CMC), occurred in Northern Sardinia after an extreme rainfall event in 2013. The possible causes of collapse are related to the conditions before and during the rainfall. Erosion and corrosion phenomena, which caused material decay and an improper water flow, have been discussed. Numerical analyses were performed to identify buckling multipliers with a finite element model simulating the effect of combined erosion and corrosion. The analysis showed a greater sensitivity in terms of buckling resistance when the soil erosion is concentrated in the lower portion of the culvert rather than in the lateral one.

Keywords: corrugated metal culvert; buckling; rainfall; culvert collapse; erosion; corrosion, buckling resistance.


Biographical notes: Linda Giresini is Assistant Professor at the University of Pisa. She obtained her PhD in 2015 and is author of about 40 publications, mainly focused on earthquake engineering and structural dynamics applied on masonry structures.

Mario L. Puppio is PhD candidate in Civil Engineering at the University of Pisa, Department of Energy, Systems, Territory and Constructions Engineering from 2014. He graduated in 2013 in Civil Engineering at University of Pisa with a master thesis entitled ‘Structural rehabilitation of r.c. residential buildings throughout multibracing steel-glass frames’.

Mauro Sassu is Associate Professor of Structural Design at the University of Pisa from 2001. He obtained his PhD in 1989 in Structural Engineering and is author of about 170 publications, Italian member of CENTC127 on fire resistance of buildings, co-editor of IF CRASC12, responsible of numerous scientific programs on seismic risk and masonry structures.
1 Introduction

The rainfall which occurred in Sardinia on 18 November 2013 was one of the most relevant events of the last decades in this Italian region (Frumento, 2014), the second largest island in the Mediterranean Sea, with an area of 23,821 km² (9197 mi²).

The isohyets map (Figure 1 (a)) shows extension and intensity of the event, whose average return period was larger than 100 years, with some peaks over 200 years. The maximum rain values in 24 hours attained 470 mm, whereas about one quarter of the island (about 6000 km²) was hit by rainfalls of over 100 mm in 24 hours. The maximum intensity of the rainfall was concentrated in the eastern part – from North to South – in the districts of Sassari, Olbia-Tempio, Nuoro, and in the south-western area. Cities, villages and rural areas were affected by numerous collapses, instabilities and functional disruptions, with numerous casualties. In particular, floods in urban, farming and grazing areas caused huge economic damages and relevant social inconveniences (Figure 1 (b)), collapses in bridges (Figure 1 (c)) and roads experienced interruption of both public and private transportation. In addition, distribution and drainage systems had been damaged with great economic losses.

One of the structural collapses occurred in a stretch of the provincial road n.38 bis, in Monte Pinu area, nearby Olbia (Figure 2). The road was constructed between 1983 and 1987; the technical-administrative testing was done in 1991.

Referring to pluviometric data, the nearest rain gauge (Putzolu) registered a rainfall amount of 190 mm in 24 hours.

The Corrugated Metal Culvert (CMC) collected water flow from the Riu de Seligheddu catch basin, with an area of 50 ha. The CMC failure (Figures 3–4) caused the collapse of the stretch of road where cars were crossing and involved loss of human lives (Giresini et al., 2015). Other similar culverts are located behind the embankment for canalising water flows (Figure 2).

These kinds of culverts are very widespread in Italy in all typologies of roads, and, even though they can be regarded as secondary structural elements, their structural conception and design are relevant for a proper functioning road (Mosco and Marconi, 1983). Their vulnerability emerges, as occurred in Sardinia in 2013, during relevant flood events. To investigate the possible collapse causes it is necessary to focus in the structural behaviour of CMC, which strictly depends on the soil–structure interaction and is influenced by the different stiffness of the soil and the pipe itself (Kang et al., 2008a, 2008b). The paper is organised in three main parts: first, the corrugated metal pipe features and damages are described, followed by considerations on the possible causes of collapse. Second, a sensitivity analysis is carried out with a finite elements model, to investigate effects of corrosion and soil erosion. Finally, the characteristics of culverts adjacent to the considered one are illustrated together with possible maintenance interventions.
Figure 1 (a) Isohyets map on 18 November 2013 and location of Olbia; (b) old roman bridge in Papuloppe (Oliena), which resisted the Cedrino river flow during the rainfall; and (c) aerial view of Olbia after the rainfall.
Figure 1 (a) Isohyets map on 18 November 2013 and location of Olbia; (b) old roman bridge in Papaloppe (Oliena), which resisted the Cedrino river flow during the rainfall; and (c) aerial view of Olbia after the rainfall (continued)

Source: Sardinia region

Figure 2 Location of the buried culverts

Source: www.sardegnageoportale.it – 2006

Figure 3 Views of the collapsed roadway

Source: Italian National Police – 19 November 2013
2 CMC features and damages description

The failure affected a stretch of road with eight similar culverts, formed by corrugated metal pipes (CMC) with polycentric cross-section (Watkins, 1975), 35/10-mm thick with horizontal diameter of 245 cm and vertical diameter of 180 cm (Figure 5).

Figure 5  Technical data sheet of the corrugated steel culvert

Source:  G. Alvito – Teravista
The corrugation was measured 152.5 mm in length and 50.5-mm high, the weight was 331 kg/ml. The culvert, whose collapse is depicted in Figure 4, was located between sections 71 and 73 (A and B in Figure 2) and was 59 m in length. The corrosion with rust at the base of the pipe, the part generally more struck by this phenomenon, is evident in Figure 6 (a): the corroded invert was a typical culvert failure (Camp et al., 2010), with loss of material and ground support, able to cause pipe instability. Squatting in the outlet part, downstream, is displayed in Figure 6 (b).

Moreover, the survey highlighted a sudden slope change at about 40 m from the collapsed roadway (Figure 7). Such discontinuity could be caused by the fall of a big rock found nearby, but also could be pre-existing due to the necessity to adapt the pipe to the morphology of the soil. No failure trace was found in the well-compacted embankment. Besides, the collapse occurred far away enough from the roadway.

**Figure 6** View of the conduit (a) inlet – upstream; and (b) outlet – downstream
3 Considerations on the collapse and possible causes

The CMC was properly designed for disposal of rainfall with return period of 1000 years according to hydraulic calculations based on the available pluviometric data (Duncan, 1979). Indeed, the catch basin had area of 0.5 km², with pipe cross-section (outflow) 3.25 m², length 60 m (Figure 8). The average slope was about 22%, even though a slope exceeding the minimum 1.0% was sufficient for proper water flow. In the survey of the pipe an angular discontinuity was found at a distance of about 40 m from the inlet cross-section. This was probably due to a structural collapse, in a location far away enough from the road, where the embankment height was small.

This angular discontinuity might have been a role in the collapse. Indeed, the sagging consequent to such a discontinuity probably helped accelerating the corrosion process, for the water collection in it. It is very likely that the pipe crushing, in this cross-section, caused the water leakage on both sides of the embankment, with consequent collapse of the roadway.

After all, the soil-steel constructive system (El-Sawy, 2003) in presence of corrugated steel culverts requires backfill material, as the pipe alone is obviously not able to bear the involved actions.

The role of the geological composition of the area was also not secondary: all natural waterways carved in granite formation convey downstream abundant sediment transport resulting from the decomposition of granite, which generated heavy abrasion.

Moreover, the high value of the average slope, 22%, increased the particles velocity exacerbating the abrasion effect. The development of erosion voids adjacent to the culvert could be an additional cause of the collapse. By increasing the volume of erosion voids and the extent of invert the elastic buckling strength could strongly decrease (El-Taher, 2009; Easley and McFarland, 1969; Moore et al. 1988; Eldib, 2009).

Several considerations can be therefore made on the possible collapse causes. A relevant role of the hardness of the soil particles, sharp-edges quartziferous granite, has to be recognised. In fact, the soil, hauled downstream by water flow, speeds up the abrasion process and then the back soil deterioration.
The abrasion first encountered the galvanised steel coating at the bottom of the pipe (Figure 9). Once the steel was in contact with water, the strong corrosion was possibly eased by the low soil resistivity and worsened by further abrasion effects.

The CMC invert oxidises up to the perforation and to the formation of greater and greater openings. The location of the angular discontinuity, at about 40 m from the entrance, appears to be the point where the openings at the bottom and on the sides are the most significant.

Those local failures could cause the instability of the flexible culvert, whose behaviour is deeply influenced by soil–structure interaction; indeed, severe deformations could occur for improper stress distributions over cross-section. In the meanwhile, the rainwater creates alternative paths adjacent to the pipe, hauling downstream the thin particles.

Erosion voids form in the area adjacent to the culvert, greater and greater over time, therefore siphoning could occur. The progression of erosion voids speeds up in case of relevant flood events. Moreover, it increases as the material accumulates within the pipe and obstructs the water flow. This increases the flow velocity, with constant flow rate.

When the voids, on the sides and behind the pipe, are large enough, the pipe basement is no longer sufficient, and bends.

Such a bending is a further reason for which the water and debris flow could not be properly guaranteed. The hydraulic pressure increases upstream with consequent relevant increasing of the erosion in the parts already corroded.

**Figure 8** Survey map of the collapsed area (see online version for colours)

The ‘reduction’ of the soil surrounding the pipe, dragged downstream by the pressurised water (relative pressure of 0.1 MPa when the pipe is completely filled with water), causes the collapse of the embankment. Moreover, debris is dragged over the pipe (Figure 10), which is subjected to crushing, modifying also its cross-section at the inlet section.
The following collapse phases, represented in Figure 11, can therefore be identified:

1. random formation of the first oxidised zones (a);
2. corrosion-erosion at the base of the culvert (b);
3. marked thickness reduction at the inlet for corrosion-erosion (c); and
4. collapse by buckling and obstruction by debris (d).

Figure 9  Views of the collapsed culvert

Figure 10  Some views of the pipes installed nearby that collapsed
Figure 10  Some views of the pipes installed nearby that collapsed (continued)

Figure 11  Phases of the collapse: (a) random formation of the first oxidised zones; (b) corrosion-erosion in the widespread basis; (c) marked thickness reduction at the inlet for corrosion-erosion; and (d) collapse by buckling and bulging of the base
4 Numerical analysis

The effects of corrosion and soil erosion were analysed with a finite element model by reducing, respectively, the CMC thickness and the soil adjacent to it. The numerical simulations have the purpose of investigating the role of geometrical dimensions, especially the thickness and the boundary conditions of the CMC on its stability.

4.1 Description of the finite element model and assumptions

Half of the CMC has been considered, due to symmetric geometry and loading configuration (Figure 12 (a)). The corrugation can be considered as it is, by modelling the pitch and the real thickness, or by adopting an equivalent thickness and an equivalent elastic modulus for the pipe. The latter hypothesis has been assumed for the sake of simplicity. According to the procedure illustrated by El-Taher (2009), the equivalent thickness $t_{eq}$ and the equivalent elastic modulus $E_{eq}$ of the culvert can be expressed as:

$$t_{eq} = \sqrt{\frac{12 \cdot E_p \cdot I_p \cdot E_{eq}}{E_p \cdot A_p \cdot E_{eq}} t_{eq}}$$

where $E_p$ is the elastic modulus, $I_p$ the moment of inertia and $A_p$ the area of the corrugated culvert. The corrugated wave is described by the function $y$ and its length $L_{pp}$:

$$y = \frac{a}{2} \sin \left( x \cdot \frac{2\pi}{p} \right) \cdot L_{pp} = \int_0^p \sqrt{1 + \left( \frac{dy}{dx} \right)^2} \, dx$$

where $a$ is the amplitude, $p$ is the pitch of the wave and $t$ is the CMC thickness. The area and the moment of inertia of the CMC are therefore:

$$A_{pp} = t \cdot L_{pp}, \quad I_{pp} = t \int_0^p \sqrt{1 + \left( \frac{dy}{dx} \right)^2} \cdot y^2 \, dx$$

The expressions of the length $L_p$, the area $A_p$ and the moment of inertia $I_p$ can now be obtained per unit of length:

$$L_p = \frac{L_{pp}}{p}, \quad A_p = \frac{A_{pp}}{p}, \quad I_p = \frac{I_{pp}}{p}$$

and used in equation (1) to calculate the equivalent thickness and elastic modulus. In the present case, values of $E_p = 200,000$ MPa, $p = 152$ mm, $a = 51$ mm and $t = 3$ mm have been adopted. The equivalent values are reported in Table 1.

In its initial configuration, the model has 1210 nodes and 560 quadratic elements (Figure 12 (b)) with minimum and maximum dimension of 15 mm and 110 mm, respectively. The program used for performing analysis is MidasGen (2012). The analysis is performed in the plane $XY$, where $X$ is the horizontal and $Y$ is the vertical axis. For what regards the boundary conditions, the nodes of the model are pinned at the base while in the profile passing by the axis of symmetry $Y$ the vertical translation is allowed, and so it is the rotation around the orthogonal axis. A reference value of vertical load
$p_v = 1.0 \text{kN/m}^2$ with a corresponding lateral earth pressure $p_v = 0.5 \text{kN/m}^2$ (coefficient of active earth pressure equal to 0.50) have been adopted (Figure 12 (a)). A specific weight of 20 kN/m$^3$ and an elastic modulus of 4.9 MPa have been assumed for the soil.  

**Table 1**  
Geometric characteristics of the corrugated profile and equivalent values

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value (mm)</th>
<th>Equivalent Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_r$</td>
<td>1.24</td>
<td></td>
</tr>
<tr>
<td>$A_r$</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>$I_r$</td>
<td>80.15</td>
<td></td>
</tr>
<tr>
<td>$t_m$</td>
<td>59.43</td>
<td></td>
</tr>
<tr>
<td>$E_{eq}$</td>
<td>916.29</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 12** (a) Loading configuration of half CMC with dimensions in mm; and (b) finite element model (*MidasGen*)
4.2 Corrosion and erosion scenarios

Two main erosion scenarios have been analysed in terms of detachment of the CMC from the adjacent soil: (i) area 1, labelled ER1, which is the lower part of the pipe, the most interested by water flow, and (ii) area 2, labelled ER2, from 40° to 80° with respect to the symmetry vertical axis (Figure 12 (a)). The erosion is simulated by physically removing finite elements representative of the soil in the region of interest.

For each of the two considered portions, the equivalent thickness calculated from equation (1) has been gradually decreased to simulate the corrosion process in a sensitivity analysis. The reduction indexes are four: 1 (not corroded thickness), 0.75, 0.50 and 0.25. The latter value better reproduces the observed situation. By contrast, the equivalent elastic modulus was kept constant. It should be noticed that the voids in the parts adjacent to the CMC can be caused either by corrosion or by initial conditions, such as those displayed in Figure 9. The analysis focused on finding a collapse multiplier from the buckling analysis for each considered scenario.

4.3 Sensitivity analysis

The analysis showed the buckling sensitivity of the CMC under the scenarios described in 4.2. Let us assume as check parameter the ratio $R$, expressed by:

$$R = \frac{\lambda}{\lambda_0}$$  \hspace{1cm} (5)

where $\lambda$ is the buckling multiplier varying according to the adopted scenario and $\lambda_0$ is the reference value corresponding to the absence of corrosion that is the initial value of thickness.
The CMC is more sensitive in terms of buckling resistance to ER1 erosion configuration, namely when there is a detachment of soil in the lower portion of the CMC (Table 2). Indeed, the residual buckling resistance is about 8% in ER1, whereas it is 50% in ER2 scenario. Nevertheless, the initial collapse multiplier $\lambda_0$ is higher by about 10% for ER1 (203.7) with respect to ER2 (179.8). However, for a reduction of 75% of the initial thickness, the two scenarios result in about the same collapse multiplier (154.0 and 159.5, respectively) (Figure 13).

<table>
<thead>
<tr>
<th>Residual thickness (%)</th>
<th>Equivalent thickness (mm)</th>
<th>Collapse multiplier (–)</th>
<th>Reduction of buckling resistance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{eq}$</td>
<td>$\lambda_0$</td>
<td>$\lambda_1$</td>
<td>$\lambda_2$</td>
</tr>
<tr>
<td>1</td>
<td>100.0</td>
<td>203.7</td>
<td>179.8</td>
</tr>
<tr>
<td>2</td>
<td>75.0</td>
<td>154.0</td>
<td>159.5</td>
</tr>
<tr>
<td>3</td>
<td>50.0</td>
<td>69.9</td>
<td>129.9</td>
</tr>
<tr>
<td>4</td>
<td>25.0</td>
<td>17.4</td>
<td>100.8</td>
</tr>
</tbody>
</table>

Figure 13 Collapse multiplier and reduction of buckling resistance for the two erosion scenarios ER1 and ER2
Those considerations permit to conclude that interventions on the lower portion would give better behaviour in terms of buckling resistance. It should be noticed that, however, that part is the most prone to the corrosion process due to its more prolonged contact with water.

5 Maintenance interventions

It should be noticed that also the nearby culverts (Figure 10) were damaged, although to a lower extent. In the area nearby that collapsed similar pipes, having different cross-section dimensions, have currently relevant degradation and, in some cases, great amounts of debris obstruct the flow.

Figure 14 (a) Metal pipe removed and replaced in 2002; and (b) metal pipe partially strengthened at the bottom with r.c. base
In 2002, about 330 m downstream far from the collapsed pipe, a similar culvert was replaced, since it caused a failure in the roadway (Figure 14). After 12 years, the pipe presents an extended oxidation. This fact could have pushed the maintenance technicians to an accurate check of all the pipes of the road, included that which collapsed on 18 November 2013.

The service life of CMCs has to be properly evaluated, even though its definition is not always simple for many factors involved: water properties and velocity, soil resistivity, tendency to abrasion and/or corrosion, etc. In the case that the water velocity is high, in low resistivity soils, a coating at the bottom of the pipe should be provided, by means of hot-mix reinforced by a steel mesh properly connected to the structure, or by means of reinforced concrete (Figure 15). The thickness of the coating depends on the soil and water type, whereas the extension of the coating, namely the angle $\alpha$ in the figure, mainly depends on the amount of design water flow and its type.

**Figure 15** Possible protecting coating at the bottom of the pipe

---

### 6 Conclusions

This paper illustrated the possible causes of the collapse of a CMC which occurred during an extreme rainfall in Sardinia (Italy). The issues of corrosion and erosion have been discussed both in qualitative and quantitative way. Four main collapse phases have been identified: random formation of the first oxidised areas, corrosion-erosion at the bottom of the culvert, thickness reduction and collapse by buckling. A sensitivity analysis has been performed with a finite element model to recreate the effect of combined erosion and corrosion. The two phenomena have been physically simulated by removing finite elements in the model, by assuming two erosion scenarios and by decreasing values of equivalent thickness. The sensitivity analysis showed that the metallic culvert is more sensitive in terms of buckling resistance when there is a detachment of soil in the lower portion (ER1) rather than in a lateral one (ER2). Indeed, the residual buckling resistance is about 8% in ER1, whereas it is 50% in ER2 scenario. Nevertheless, the initial collapse multiplier $\lambda_0$ is higher by about 10% for ER1 with
respect to ER2. Finally, considerations on the actual conditions of culverts nearby that collapsed and maintenance interventions were proposed, by highlighting the need of carefully evaluating their residual service life.

References

Mosco, V. and Marconi, G. (1983) Criteri di calcolo e dimensionamento dei sottopassi e tombini in acciaio, Estratto dalla Rivista Acciaio no. 5, CISIA, Milan. [In Italian]  