Site investigations on cavernous limestone for the Remouchamps Viaduct, Belgium

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POOR GROUND CONDITIONS on cavernous limestone created severe difficulties at the sites of four piers of the Remouchamps Viaduct. The discovery, during excavations for foundations, of large open cavities prompted a major re-appraisal of site investigation procedure, and also some redesign of the viaduct structure.

Introduction

The Remouchamps Viaduct carries the Liège to Arlon section of the E9 motorway across the Amblève valley, incised into the Ardennes plateau of southern Belgium. It is 939m long and carries four lanes of traffic, 81m above the Amblève River. Of its eleven piers and two abutments, seven are founded at least partly on limestone, and work associated with the difficult ground conditions was responsible for a 15% increase in overall cost. The viaduct was completed in 1980 at a cost of 1400 million Belgian Francs[1].

Site geology

Bedrock in the Remouchamps area consists of sandstones, limestones and shales of Devonian age. They are strongly folded, so that they are locally vertical or overturned, and they contain many small faults. The sandstones are generally massive and strong, but the shales are commonly altered and weathered to considerable depths, and are of low bearing capacity.

The limestones at the site were already known to be generally massive, fine grained and strong, but also to have been subjected to extensive karst solution. Open surface sinkholes are not abundant, but there is intense sub-soil solution with open fissures at depth. Many caves are known in the region, including the Remouchamps show cave (Fig. 1) which has 2 800m of mapped passages, mostly in excess of 5m in diameter[2]. Within the limestone sequence, there are zones of shale interbedded with a minor proportion of impure limestone; these include the Macigno melange, consisting of a limestone-shale conglomerate, and some black dolomite beds.

Superficial deposits consist mainly of thin sand and gravel alluvium, together with higher level terraces of similar material. Many of the limestone slopes are covered with very thin clay colluvium.

Initial site investigation

The line of the motorway was determined by topographical constraints, and it was recognised that a major viaduct across the Amblève valley would have to be founded partly on limestone, partly on shale and partly on sandstone. After a desk study to determine the broad geological structure, a programme of cored boreholes was carried out with laboratory testing of the cores. At least four boreholes were placed on each pier site.

A seismic refraction survey was used to explore the depth of the alluvial terrace at the Arlon end of the viaduct (Fig. 2). A microgravimetric survey was not used on the limestone outcrop; a similar survey had been done at the site of the adjacent Secheval viaduct, but had been found to have limited value in an area of such structural and topographic complexity[3].

A pinnacled rockhead on heavily fissured limestone was found at the site of pier 6, which was therefore moved 27m towards Arlon off the limestone. At both the site for pier 5 and the new site for pier 6, weathered shales indicated the need for spread footings and low net loadings. Elsewhere the borehole survey gave no indication of unsound rock, and excavation work commenced.

The north abutment

Excavation for the foundations of the north abutment revealed an open cave just below the surface; its single passage was 2-3m high and wide and descended steeply to the west before, becoming choked 65m from its entrance (Fig. 3). Eight boreholes had been drilled on the site, but all had missed the cave. Six out of the eight bores recorded solution fissures and cavities in the limestone, though almost all were less than 40cm across, and they revealed no pattern to indicate more extensive solution.

Shuttering was placed in the cave 18m below formation level, and the cave was then filled with a fluid cement from there up to a level of −5m. Weathered rock round the cave mouth was removed to a depth of 5m and the whole then replaced with a lean concrete, providing a solid base on which the foundations were laid.

Pier number 2

After four boreholes had revealed no indication of poor ground, excavation to formation level exposed the roof of an open cave passage. Figure 4 shows how this was the upper part of a complex system of cave passages, directly below the pier site, which had been missed by all the boreholes. The upper passages in the cave consist of solution rifts and wider bedding controlled chambers, long abandoned by any stream; their roofs are collapsing, leaving their floors covered in breakdown debris, and they may continue eastwards beyond the boulder chokes which block them. The lower passages contain an active streamway, fed by various rifts in process of active solution.

Borehole 59 would have revealed the cave if it had been a few metres deeper, and borehole 12 would have intersected the lower cave at a much greater depth. Boreholes 16 and 17 both passed between open cave in the upper system. The logs from boreholes 59 and 17 both record open or clay filled fissures in their lower parts, but these have no apparent relationship to the revealed cave.

The volume, extent and complexity of the cave system, in a zone of extensively corroded rock, precluded a massive concrete filling. The site of the viaduct pier was therefore moved 13.5m towards Arlon, after detailed ground examination; construction could then proceed after only a small part of the cave had been filled. And at the same time, the extent of site investigation on the limestone was greatly increased with respect to the other pier sites.

Revised site investigation

When the extent of the solution cavities beneath pier 2 was recognised, much more intensive exploration was instigated at all the pier sites on limestone. The principle technique employed was probing with precise measurements of the rates of penetration; though this was of limited value in other ground conditions, it was found to be inexpensive and very effective for identifying limestone solution voids, which were either open or filled with young unconsolidated sediment. It was recognised that karstic solution cavities could exist anywhere, in no recognisable pattern; also while small voids were hazardous at shallow depths, larger voids could be tolerated at greater depths. Consequently, probes were drilled to 6m depth on a 2m grid, with drilling to 30-50m depth on a 10m grid. In practice, there was some flexibility in both the grid pattern, and the depth penetrated.

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TABLE I. COMPARISON BETWEEN SITE INVESTIGATION TECHNIQUES EMPLOYED AT PIER AND ABUTMENT SITES ON LIMESTONE AND ON SANDSTONE

	On limestone	*On sandstone*
Number of foundation sites	5	6
Number of cored boreholes	31	23
Number of uncored probes 6m deep	169	0
12-20m deep	90	4
30-50m deep	49	8

Some zones of rapid penetration were then checked by downhole cameras, but the scope of this was limited by the clay fills in the caves. Table 1 shows the extent of drilling on the limestone, in marked contrast to that carried out on the non-cavernous sandstone outcrops. In the event, the intensive grid drilling did not discover any further large cavities to match those beneath the initial site of pier 2.

The final appraisal of the limestone recognised a pinnacled rockhead broken by conical depressions containing clay and corroded limestone blocks. This passed downwards into a zone of limestone with clay filled pockets and caves of extremely variable morphology. At greater depths the main solutional openings in the limestone were corroded fissures, creating a network system, and locally enlarged to shafts and galleries 1-2m in diameter. The most intensive cavitation was found in the limestone close to the contact with shale or Macigno beds. This was to be expected, because corrosive surface water collects on the impermeable rocks, and flows onto the limestone to immediately sink into fissures where it is then capable of extensive solutional action; the underground boundary also acts as a barrier to groundwater flow within the limestone, deflecting water to flow parallel to it. Solutional activity and consequent cavitation is therefore concentrated in the limestones adjacent to the impermeable outcrops. An additional notable factor at Remouchamps was the marked variability of ground conditions; at the northern abutment and pier 2 sites significant caves were found, while the intermediate site of pier 1 was on sound rock.

The above description might apply to any site on karst limestone in temperate or tropical environments. The depths of the pinnacles and of the more intensely cavernous zones, relate to local factors of topography, drainage and climatic history.

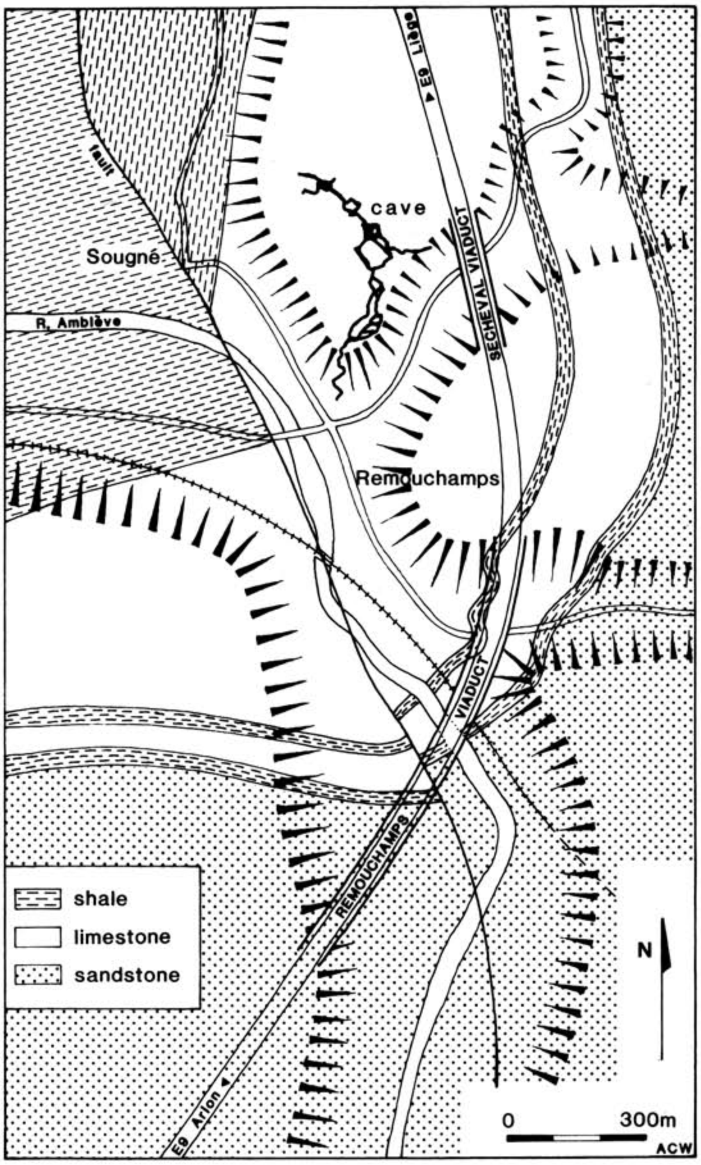
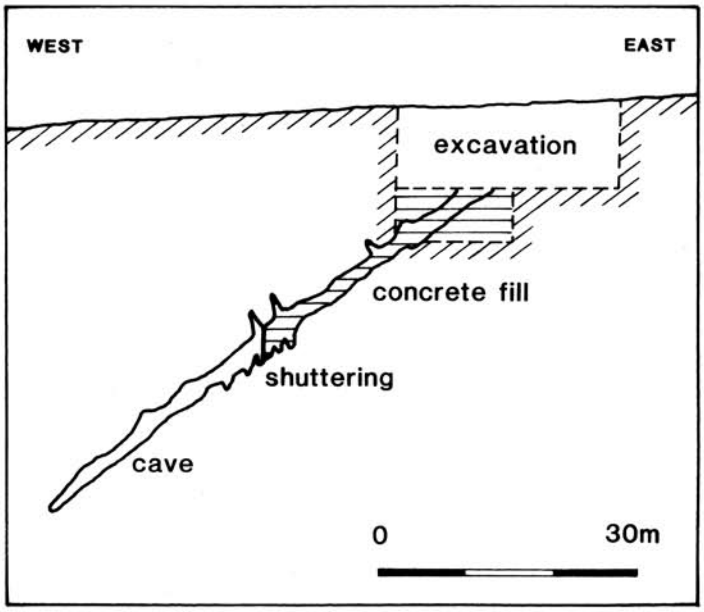


Fig. 1 (Left). Topographic and geologic map of Remouchamps Viaduct area

Construction and foundation design

At all sites, the limestone required some treatment and improvements. The depth of the main solution zone was too great to place formation level below it on unweathered rock; a limited net of karstic cavities is likely to occur throughout the thickness of a limestone. Clay pockets in exposed rock were cleared out, and all fissures in the limestone were grouted with concrete, using plugs in some cases to restrict dispersion. Grout was also injected into the exploration boreholes, with a mean take of 117kg in a mean depth of 17m. These techniques proved successful on the sites of piers 1, 3 and 4, and on the new

Fig. 3 (Below). The cave at the north abutment



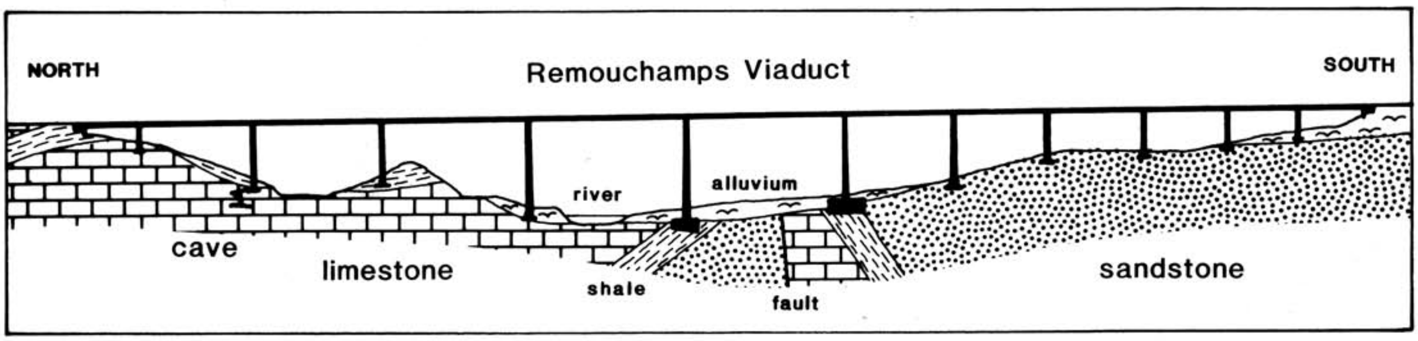


Fig. 2. Long section of Remouchamps Viaduct and bedrock geology

site of pier 2 relocated away from the cave system.

At pier 5, limestone and dolomite provided a good foundation at a depth of around 8m, but part of the footing was unavoidably on shale. This was heavily weathered and required removal to a depth of 15m before an assymetric concrete pad could be placed inside a diaphragm wall.

The initial site for pier 6 proved to be over limestone bedrock, but directly above a buried sinkhole 9m deep and 10m in diameter cut into a heavily pinnacled rockhead beneath 8m of alluvium. The extremely corroded nature of the ground made it unsatisfactory, and the pier was relocated onto a rockhead of shale and sandstone. Even on the new site, the calcareous shale was so heavily weathered that it would accept only a very limited net loading, and the pier had to be founded on a cellular caisson, 29m in diameter and 13m deep, sunk into place.

Conclusion

The foundation conditions at the Remouchamps Viaduct provided an excellent example of the unpredictability of the nature of cavernous limestone. In general terms, it is impossible to predict the extent of solution cavities in unexposed limestone beneath any given site. However, at the Remouchamps site, an indication that cavities were even more likely to occur than normal could be taken from both the presence of known major caves nearby and also the location of the site close to the limestone margin. In such circumstances there is no alternative to detailed and exhaustive site investigation with high density borehole grids. Geophysical exploration of cavernous limestone is very difficult to interpret, and normally can act only as an aid to efficient planning of a more conclusive drilling programme. Boreholes are expensive, but even a major drilling programme, carried out at an early stage in project planning, is economically viable when it can eliminate even more expensive delays to the construction timetable.

The small numbers of boreholes in the initial viaduct site investigation were inadequate – as demonstrated by subsequent events at the north abutment and pier 2. With the benefit of hindsight, the hundreds of probes employed in the second phase could be deemed overreactive. But large numbers of drilled holes are unavoidable to satisfactorily prove that hazardous cavities do not exist. If the roof of the cave at pier 2 had remained unexposed, just below formation level, the consequence of later collapse and failure could have been extremely serious. In view of the low cost of probing by destructive drilling, compared to total project costs, excessive site investigation in areas of cavernous limestone is probably impossible.

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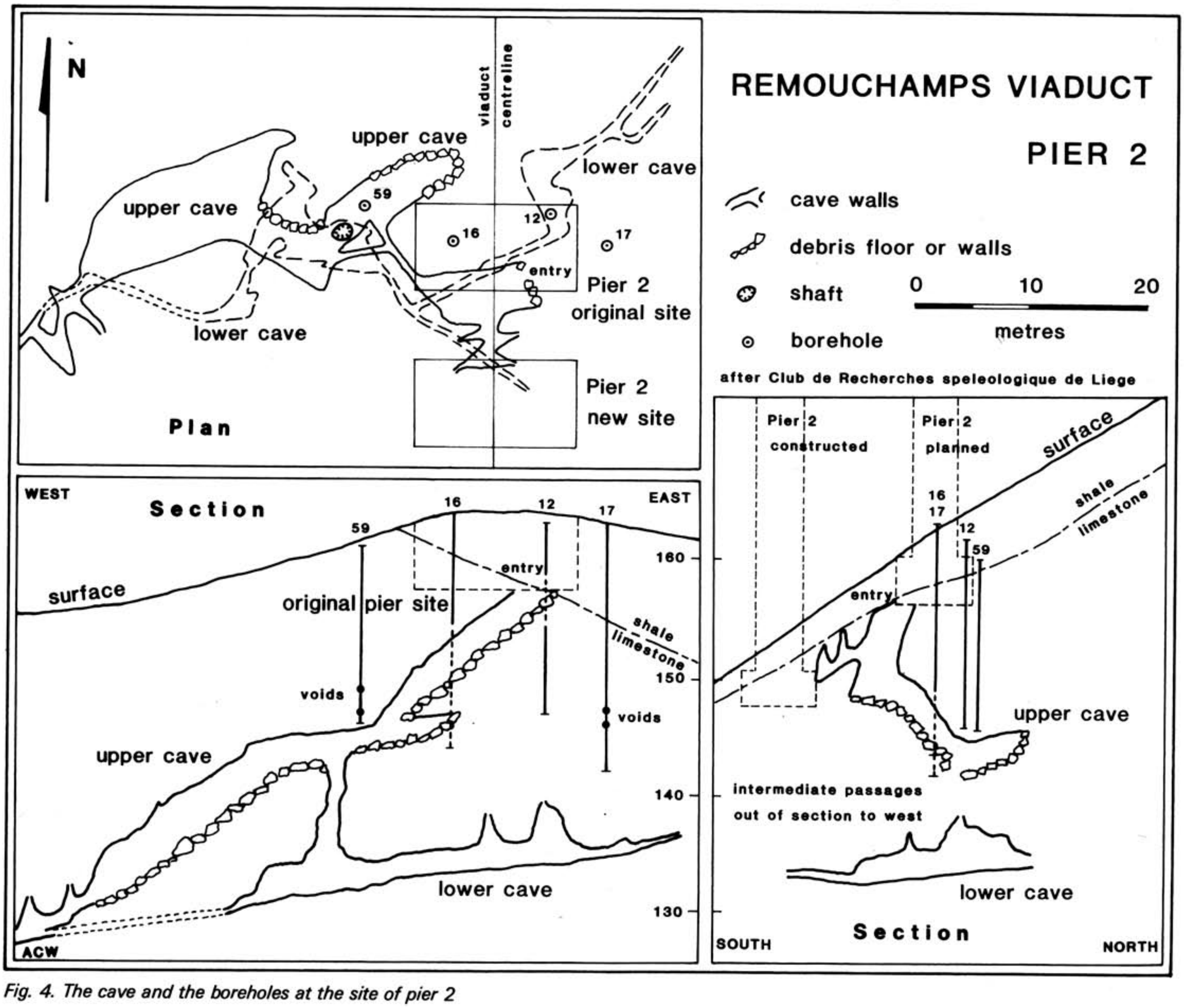

Fig. 4. The cave and the boreholes at the site of pier 2