Soil–Structure Interaction in Sidi Rached Masonry Bridge

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Abstract

The Sidi Rached Bridge was built in the early 20th century across the Rhumel canyon in the centre of Constantine, Algeria. The bridge, with its 27 arcades spanning up to 68 m, is a famous city landmark and one of the main cultural heritage centres of Algeria as well as the largest masonry structure of this type in Africa. The eight spans on the right bank have been in distress for over 50 years from intermitting slope instability. The problem was addressed and temporarily solved on more than one occasion. After 30 years of being relatively uneventful, a landslide in 2008 caused severe damage to all the piers on the right bank and the near collapse of one arcade. A new campaign for assessment, reconstruction and strengthening has therefore been undertaken. This paper presents the results of the study and the repair works carried out so far, mostly at the foundation level, while structural monitoring and further strengthening are being performed on this historical monument that still provides a vital link in the hearth of one of the most populous cities of North Africa.

Keywords: masonry bridges; slope instability; numerical modelling; rehabilitation; external post-tensioning.

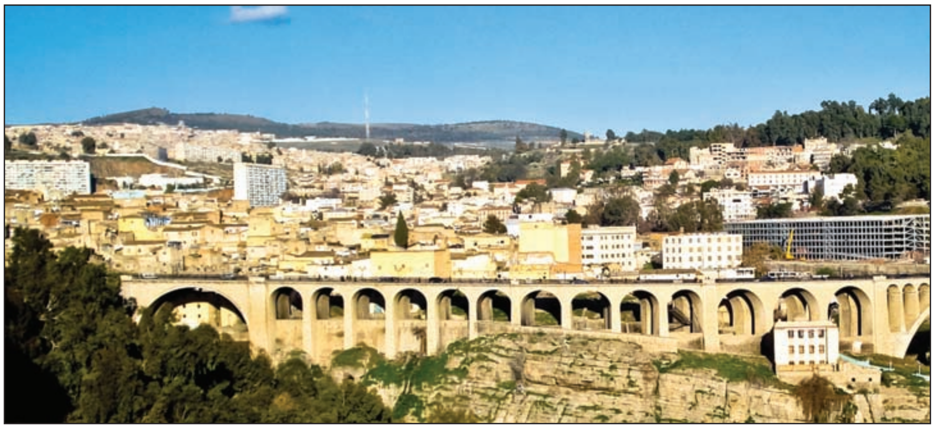

Fig. 1: The Sidi Rached Bridge seen from upstream (right bank on the right)

Introduction

The Sidi Rached Bridge, built between 1907 and 1912, was designed by the French engineers Aubin Eyraud and Paul Séjourné on the basis of a scheme already used in similar structures during that period, such as the Adolphe bridge in Luxemburg.[1] Constantine, also known as the "City of Bridges", has another three historical bridges crossing the Rhumel canyon, two are suspension bridges[2] and one a concrete arch bridge, all of them built in the early 20th century and still vital to the city and its traffic management.

Contrary to the other structures, the Sidi Rached foundations are partly built into the limestone bedrock (left bank) and partly on an argillite formation that sits on the limestone on the right bank. This area and others with similar geology within Constantine are prone to instability. These slope instabilities have been exacerbated by the leakage of the city aqueducts and the deforestation of the city slopes to make space for new housing localities required for the booming Algerian population.

The Sidi Rached Bridge showed the first signs of damage in the early 1960s. The slope instability of this side of the Rhumel has been constant since then. In over 50 years, the bridge abutment has crept over half a metre downhill. Large cracks have opened in the piers on the right bank but without critically affecting the statics of the arches. This is certainly due to the intrinsic flexibility of the tall masonry piers but also to the planimetric curvature of the bridge (deck) that has allowed it to buckle instead of collapsing, as detailed in the following text.

When the slope instability spiked in the 1970s, the first arcade spanning the abutment to the first pier had to be severed and replaced with a simply supported buffer span. Over the years, the joints at both sides of the buffer deck became jammed and the abutment had started to push once again against the rest of the viaduct. In 2008, the situation became grave, with cracks appearing at the pier base in the centimetre range with incipient collapse of one arch.

The Constantine's Public Work Authority finally decided that a major intervention was required. The investigations, studies and strengthening works that followed are summarised in this paper. Work is still ongoing and the bridge has been closed and reopened to traffic according to the different phases of the works.

The Bridge

The Sidi Rached Bridge is a stone masonry arch bridge made of 27 arcades. The typical arcade has a clear span of roughly 9 m, four have 16 m spans, one has 30 m span and the main arcade crossing the Rhumel has a clear span of 68 m standing at 102 m above the bottom of the canyon. The bridge does not have solid arcades but is made of two parallel ones, 4 m wide, 4 m apart for a total platform width of 12 m. Each support is therefore made of two tapered piers with a rectangular section measuring 4×2 m at the arc sets. Pier height varies from 10 to 20 m approximately. The bridge deck between the two parallel arches is supported by reinforced concrete transverse beams, spaced at 2 m at the centres (see *Fig. 1*).

The bridge's stone-facing consists of a very tough limestone rock with filling made of stone rubble and mortar. Pier foundations are built into the bedrock except for the first four piers on the right bank where the bedrock is 15 to 5 m deep below the ground level. The bridge does not present any sign of ageing except for the damage on the approach spans on the right bank caused by the slope instability. Traffic is intense but heavy axle loads are not particularly frequent as the bridge is connected to the heart of the city. Climate is mild and rain scarce and therefore icing-deicing phenomena are very rare. Although built in a seismic area, no major earthquakes have struck the region since the bridge construction.

Geology and Hydrogeology

The Rhumel canyon cuts across the limestone formation that is part of the "Néritique Constantinois" geological domain (Upper Cretaceous).[3] This formation consists of grey to whitish micritic limestone, widely exposed in layers of various thicknesses along the steep banks of the canyon. From a geostructural point of view, the limestone formation forms the flank of a monocline fold that plunges southeast towards the right bank of the valley, with a gentle dip of 5°.

A pelitic formation, discordant and probably overthrusted, lies above the limestone layers on the upper part of the right bank, from the edge of the canyon up to the plateau of Mansourah. The pelitic formation is composed of argillites, shales, marls, and often laminated schist. The superficial portion of this formation has been affected by deep weathering and the material has been transformed to a clay plastic soil. The abutment and the first three piers rest on the pelitic formation while the other piers on the limestone layers (see *Fig. 2*). From a hydrogeological point of view, pelitic formation is made up of fine-grained materials with medium to low permeability. Piezometric monitoring and on-site tests have shown that the underlying limestone layers are generally less permeable than the marls (due to the low fracturation) and represent the "aquiclude" of the water table. Water table level has been found to be close to the limestone-marl layers and may quickly rise up during intense rainfall.

Damages and Repairs: A Brief History

Although slope instability of the site was already known during construction, serious damages developed only in the 1960s. When slope instability rehabilitation was kick-started, a series of interventions were carried out on the bridge. When exactly these works were done is however not clear because of lack of documentation. The major and possibly more successful intervention has been the removal of the first arcade to allow for the abutment to slide without pushing against the rest of the viaduct. The first arcade was replaced with a simply supported composite deck and the second arcade closed with shear walls so as to resist the horizontal forces of the following arches. In order to limit the displacement of the abutment, soil anchors were drilled into the bedrocks and anchored against the abutment front wall. A drainage pit was also bored in front of the abutment with radial drains fanning out into the pelites. The strengthening works addressed not only the abutment, stability of the first eight piers (four alignments) was also tackled by casting a network of reinforced concrete beams that connected the foundations of these piers and propped them downhill against the limestone surface (see *Fig. 3*). All these remedies appeared sufficient because the bridge was stable and unaffected by the slope instability for the next 25 years roughly while all the houses in the surrounding area were inexorably crumbling.

In 2008 the bridge started to develop very wide cracks at the pier bases. The damage extended to the fourth arcade followed by crushing and spalling of the stone masonry of one arch (see *Fig. 4*). However the bridge could not be closed to traffic because the city was dependent on this bridge to get across the Rhumel canyon that cuts through its centre.

The Numerical Simulations

Although quite simple with hindsight, the kinematics and mechanics of the damage were not clearly identified in the studies carried out in the 1970s. Besides, the mechanics of the new damages that started in 2008 appeared to differ from the previous ones; while the recent cracks were wide the previous damages could not be detected (except for the collapse of the first arcade). The cracks and the displacements that spiked in 2008 were so large that it was decided to start taking topographic surveys of the structure every month. These readings turned out to be extremely useful.

A three-dimensional (3D) finite element model of the bridge was set up.[4,5] In order to keep the size within acceptable limit, only the arcades on the right bank and the main arcade over the Rhumel were remodelled (see

Fig. 3: Existing reinforced concrete beams connecting the foundations of the piers

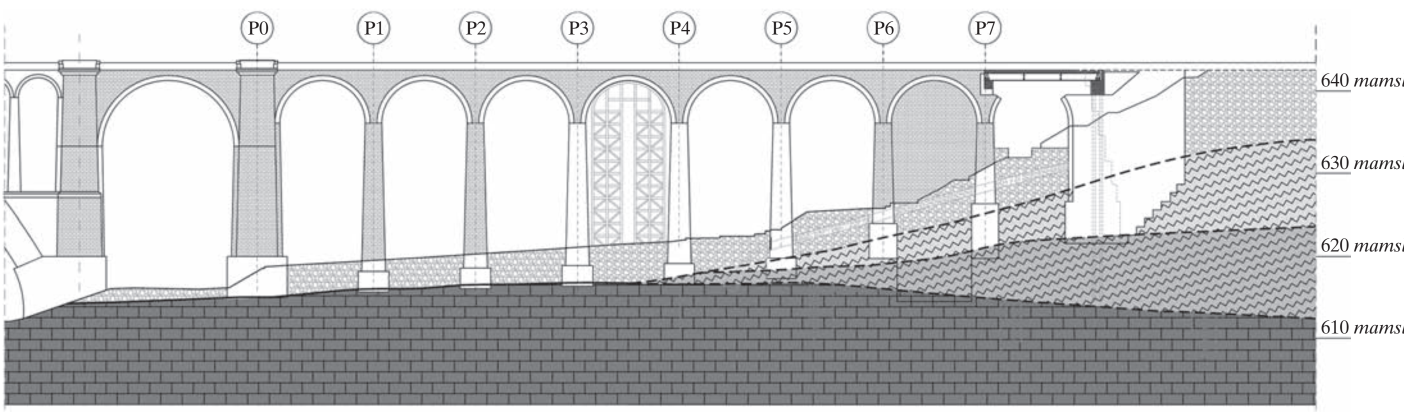

Fig. 2: Geological section of the right side of the Sidi Rached bridge

Fig. 5). The effect of the rest of the bridge (the other 18 arcades on the left bank) was accounted for with boundary (spring) elements. The first seven arcades on the right bank were modelled with brick elements, and the main arcade with beam elements. Given the urgency to understand the mechanics of the damage, a linear elastic constitutive behaviour was applied associated to an iterative element elimination procedure in order to explain the crack development and splitting failure in the masonry elements. A threshold value of 0,1 MPa in tension and 8 MPa in compression was assumed based on literature. With only three iterations the kinematics of the damage mechanism was immediately clear. The approach spans are in a curve, precisely quite a narrow curve (105 m radius). When a push was applied from the abutment, the bridge buckled and swayed outwards. Very wide flexural cracks formed at the pier bases (see *Fig. 6*). All this was confirmed by the topographic readings; the outward sway of the deck is currently 200 mm circa. Crack openings up to 20 mm at the pier base are consistent with a rigid body kinematics. At the centre of the curve, a plastic hinge developed in the deck with crushing of the inside (downstream) arch. The likely failure scenarios had to be identified so as to carefully evaluate the possibility of keeping the bridge open for pedestrian and light vehicles during the repair works. Although very large, the sway of the deck could not cause any collapse by triggering P-Delta (P-D) effects. Also the crushed arch between Piers 4 and 5, although severely damaged, was held in place by erecting provisional supports (scaffoldings). The numerical simulations clearly identified the brittle failure of the piers as the most critical scenario. Rotations at the pier bases are so high that the compression zones of these sections are very thin and subjected to very high stress, close to stone crushing, due to the bridge self-weight. The numerical predictions were confirmed in the following months by the splitting cracks that developed in the stone-facing of four piers, where the kinematics of the bridge inflicted the largest rotations at the base sections.

Fig. 4: Crushing of the arch between Pier 4 and 5

Emergency Propping and Slope Stabilization

The repair works were phased so as to address the short- and long-term necessities of the structure and the city traffic. Given the magnitude of the landslide no quick fix could be found and the repair works on the bridge had to be accommodated according to the timing required for the slope stabilization. However, there was no guarantee that the latter could be achieved before the bridge was completely wrecked. The Constantine's Public Work Authority had dismissed an earlier proposal to demolish the arcades on the right bank and replace them with a new structure capable of withstanding, absorbing or avoiding the slope instability.

The first interventions were the temporary propping of the crushed arcade in order to allow the transit of pedestrians and cars on the bridge. Second intervention, in summer 2011, was the removal of the old buffer beam that was jammed and its replacement with a new deck, shorter, lighter and with enlarged gaps to allow for differential displacement of the abutment.

Unfortunately, during fall and winter from 2011 to 2012 the slope sliding peaked again requiring other two arcades to be propped and the most damaged piers had to be reinforced with steel profiles and transverse prestressing so as to prevent their collapse (see *Fig. 7*).

Attempts to alter a slope from sliding downhill with rigid retaining structures capable of absorbing a push is very often ineffective, especially in the long run, as in the case of the works carried out on the bridge in 1970. Given the speed of the sliding some intervention had to be done though, before it was too late. A series of inclined micropiles (60) and soil anchors (70) were bored in between the piers so as to prevent

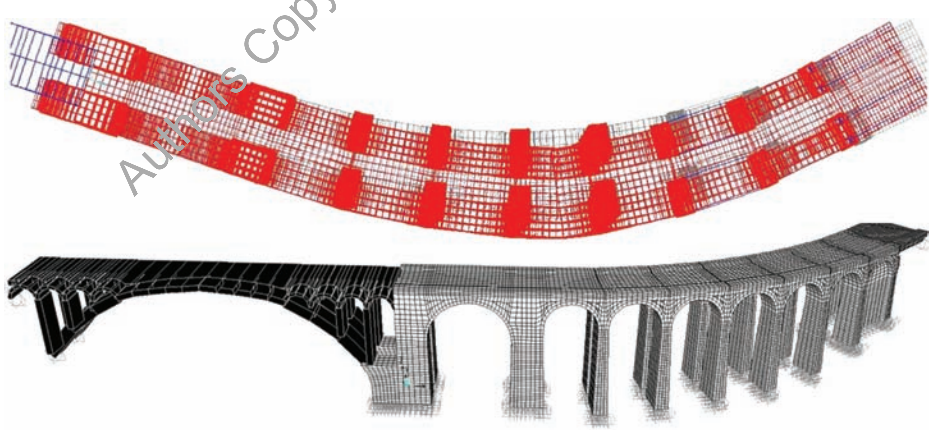

Fig. 5: The finite element model of the Bridge: (bottom) the undeformed mesh; (top) the bridge deformation in plan (amplified by factor of 20)

Fig. 6: Cracks at the pier bases caused by the section rotation: (left) mode-I opening on the tensile side; (right) splitting cracks on the compression zone

Fig. 7: Emergency propping and pier jacketing with steel profiles and external postensioning

further sliding of these foundations. The main drawback of these works is the vibrations generated by boring into the limestone that have a negative impact on the damaged masonry. Nonetheless, if these interventions continue to prove successful, together with the complete kinematic decoupling of the abutment, they should prevent further deformation of the bridge.

Halting the abutment from sliding downhill with soil anchors was deemed unfeasible. The abutment is seated on 15 m of pelites that slide onto the underneath limestone. In this part of the slope, stabilization was hoped to be achieved by coupling drainages with a stiff retaining structure. This structure consists of two pits made with large diameter bored piles driven into the limestone. The two pits were connected by a trench. This structure provided the working space for boring sub-horizontal drainages into the pelites and was also capable of slowing down the slope sliding while disconnecting the uphill part of the slope from the downhill thereby preventing the land slide from reaching the rest of the bridge.

Bridge Monitoring and Rehabilitation

With the foundation strengthening and drainages almost completed, long term planning of the interventions to be carried out on the bridge is being discussed with the client. A monitoring system will be set up based on an automated topographic reading of the structure displacements. These high precision readings are to be carried out during the rainy season until spring 2014. These readings will indicate whether the interventions on the foundations are effective and if the structure is not subject to further imposed deformations.

Only then, the collapsed arch between Piers 4 and 5 can be demolished and reconstructed. The interesting and critical aspect of this phase of the work is that, based on the numerical analyses, the bridge deck is still carrying a compression force of 900 t. This force did not decrease substantially upon the removal of the buffer deck between the abutment and Pier 1 because the shear walls built between Piers 1 and 2 prevented the structure from being set back. Demolishing the arcade between Piers 4 and 5 will release the axial compression in the deck and the bridge will set back and partially recover from the swayed and tilted position.

With the halting of the slope instability and the arcade reconstruction between Piers 4 and 5, strengthening of the bridge will be finally addressed. The piers are to be injected with cement mortar so as to improve strength and ductility of these elements. The interventions on the piers on the right bank (damaged ones) are likely to continue on the piers on the left bank. No interventions are planned for the arcades and the deck except for waterproofing, already implemented during the early stage of the works.

Is the Sidi Rached Bridge vulnerable to seismic events? The bridge did survive undamaged in the 1985 earthquake, the strongest one in the last century (magnitude VIII in the Medvedev–Sponheuer–Karnik (MKS) scale). Recent studies[6] have put Constantine's Peak Ground Acceleration (PGA_{475}) between 0,15 and 0,2 g, other more pessimistic estimates go up to 0,25 g, Based on these facts and studies, seismic strengthening of the bridge is not a priority although the structure is certainly vulnerable to worst-case scenarios. Besides, seismic strengthening of such huge structures is highly expensive as it requires very extensive interventions on the masonry of the piers and the arches. Total masonry volume of the Sidi Rached Bridge is a staggering 5500 m^3.

Conclusions

Stone and masonry arch bridges are particularly vulnerable to soil instability and differential settlements. These structures, especially if part of a national heritage as in the case of the Sidi Rached Bridge, should be continuously monitored so as to be ready to undertake the necessary measures in due time. Arresting soil instabilities such as landslides affecting the various zones of Constantine require significant resources and time. These structures may not be capable of withstanding the imposed deformation before these instabilities are halted and their cause removed.

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SEI Data Block

Owner/Client:
Constantine Municipality/Direction Travaux Public

Designer:
INTEGRA s.r.l., Rome (Italy)

Execution:
SAPTA, Algiers (Algeria)

Foundation strengthening:

– Micro-piles (m):	650
– Soil Anchorage (m):	1380
– Sub-horizontal Drains (m):	1440
Completion Date:	Spring 2015