Second Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2013

Rescuing the Sidi Rached Bridge

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ABSTRACT: The Sidi Rached Bridge in Constantine, Algeria, is the largest masonry bridge built in Africa. The bridge, built in the early 20th century connects the two side of Constantine crossing the Rhumel canyon with a 68 metre span running 102 metre above the underneath river bed. The bridge is made of 27 arches, the 8 on the right bank have been suffering for over 50 years, from an intermitting slope instability. The problem has been addressed and temporarily solved few times now. All the attempts tried to anchors the pier foundations to the bedrock while reducing the cause of soil instability with drainages. During the ’70, the downhill displacement of the abutment was so high that the structure had to be disconnected severing the first arcade and replacing it with a simply supported buffer steel girder. After 30 years of relative calm, the land slide peaked again in 2008 causing severe damage to al the piers on the right bank and the near collapse of one arch. A new campaign of assessment, reconstruction and strengthening is currently being carried out. The damage mechanism taking place in the structure has been fully understood thanks to high precision topographic readings and a 3D non-linear finite element model of the bridge. A more demanding task will be the attempt to halt the slope sliding and revert the damages in the structure before is too late. The paper presents the results of the study and the first interventions taken while monitoring, studies and works are being carried out on this historical monument that cannot be closed to traffic without major disruption to the economy of Constantine, one of the busiest town in North Africa.

1 INTRODUCTION

The Sidi Rached Bridge, built between 1907 and 1912 in Constatine, was designed by the French engineers Aubin Eyraud and Paul Séjourné according to a scheme already used in similar structures in that period such as the Adolphe bridge in Luxemburg [1]. With a total length of 450 metre circa, standing over 100 metre above the bottom of the Rhumel canyon, the Sidi Rached Bridge is still vital to the everyday life of people living in Constantine that use this bridge to cross the deep canyon cut by the Rhumel river right in the city centre. 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, all of them built in the early 20th century and still vital to the city life and traffic management.

Contrary to the other structures, the Sidi Rached foundations are part built into the limestone bedrock (left bank) and part on an argillite formation that sits on the limestone on the right bank. This side of town as well as other areas within Constantine with similar geology are prone to instability. This slope instability has been exacerbated by the leakage of the city aqueducts and the deforestation of the city slopes to make space for the new housing required by the booming Algerian population.

The Sidi Rached bridge showed the first signs of damage in the early ’60. The slope instability of this side of the Rhumel has never stopped since then. In over 50 years certain areas have moved over half a metre downhill. As a matter of fact it is amazing that the bridge is still standing in spite of these displacements. Large cracks have opened in the piers over the years on the right banks without seriously 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 squash, as better detailed in the following chapter.

When the slope instability spiked in the ’70, the first arcade connecting the abutment and the pier had to be severed and replaced with a buffer composite span capable of absorbing the extremely high down-hill displacements of the abutment. Over the years, the joints at both sides of the buffer deck have jammed and the abutment has started to push once again against the rest of the viaduct. In 2008 the situation became dramatic, with cracks opening in the piers in the centimetre range but also with the incipient collapse of one arch.

The Constantine’s Public Work Authority finally decided a major intervention was required. The investigations, studies and strengthening works that followed are summarised in the paper. At the time of going to press, the works have not finished yet and the bridge is being closed and reopened to traffic according to the different phases of the works.

2 THE BRIDGE

The Sidi Rached bridge is a stone masonry arch bridge made of 27 arcades. The typical arcade has a clear span of 9 metre roughly. There are another four arches with 16 metres span, one with 30 metre span and the main arcade crossing the Rhumel with a 68 metre clear span. In order to reduce the weight of the structure, the bridge does not have solid arcades but it sports two parallel arches 4 metres wide 4 metres apart for a total platform width of 12 metres. Therefore each support is made of two tapered piers with a rectangular section measuring 4x2 metres at the arcs sets. Piers height varies from 10 to 20 metres circa. The deck between the two parallel arches is supported by transverse reinforced concrete beams spaced at 2 metres centres.

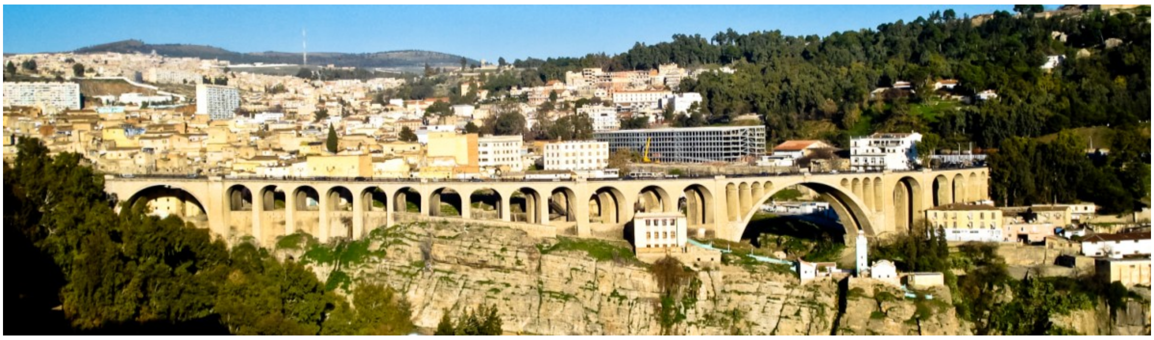

Fig. 1: The Sidi Rached Bridge seen from upstream (right bank on the right)

The stone facing of the structure is made of a very tough limestone rock. Filling is made of rubble stone and mortar. Pier foundations are built into the bedrock except for the first 4 piers on the right bank where the bedrock is 15 to 5 metres deep below ground level. The bridge does not present any sign of ageing except for the damage on the approach spans caused by the slope instability on the right bank. Traffic is intense but heavy axel loads are not particularly frequent as the bridge leads to the very city centre. Climate is forgiving and water scarce. Icing-de-icing phenomena very rare. Although seismic area, no major earthquake happened since the construction of the bridge.

2.1 Geology and hydrogeology

The Rhumel canyon, is excavated in a limestone formation that belongs to 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 geo-structural point of view, the limestone formation forms the flank of a monocline fold that plunges to SE (towards the right bank of the valley) with a gentle dip of 5°. A pelitic formation, discordant and probably overthrusted, lies above the limestone on the upper part of the right bank, from the edge of the canyon up to the plateau of Mansourah. The pelitic formation is formed by argillite, shale and marls, frequently schisted and laminated. The superficial portion of this formation has been affected by a deep weathering and the material has been transformed in a clay-plastic soil. The abutment and the first three piers lay on the pelitic formation while the other piers on the limestone. From a hydrogeological point of view, the pelitic formation is formed by fine-grained materials, with a medium to low permeability. Piezometric monitoring and on-site tests have showed that the underlying limestone 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 measured close to the contact limestone-marls and it may quickly rise up during intense rainfall.

2.2 Damages and repairs

Although slope instability was known from the construction time, serious damages developed only in the '60. Certainly instrumental must have been the construction of the railway line hundred metres beyond the right abutment. Meteoric water does infiltrate much more easily along the tracks. Other factors must have kicked in; the construction frenzy of those years certainly altered the equilibrium of that part of Constantine. But the instability may also be pre-existent and quiescent for a while.

When slope instability kick off, a series of interventions were carried out on the bridge. The exact timing of these works is not clear though because of lack of documentation. The major and possibly more successful intervention has been the severing of the first arcade to allow 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 a shear wall 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. Also a drainage pit was bored in front of the abutment with radial drains fanning out from it into the pelites. The strengthening works did not address only the abutment though; stability of the first 8 piers (4 alignments) was also tackled casting a network of reinforced concrete beams that connected the foundations of these piers and propped them downhill against the surfacing limestone. All these remedies must have worked for a while since the bridge seemed to be stable and unaffected by the slope instability for the following 25 years roughly while all the surrounding houses were inexorably crumbling.

The reason because these remedies did not last longer is due to a number of factors that can be pointed out although the killing one is anyone guess. The soil anchors must have rusted out and lost their anchoring effect; the joints of the buffer beam jammed because of lack of proper maintenance and therefore the abutment started again to push against the rest of the viaduct; the concrete beams cast between the first 4 piers buckled as found during the new repair works, showing the slope instability to extend downhill pass the abutment. In 2008 the bridge started to bulge with very wide cracks opening at the pier bases. The damage extended to the 4th arcade with crushing and spalling of the stone masonry of one arch. Still the bridge could not be closed to traffic since the city centre needed this bridge to get across the Rhumel canyon.

Fig. 2: Crushing of the arch between Pier 4 and 5

Fig. 3: Wide flexural cracks at piers bases

3 FAILURE MECHANISMS

Although quite simple with hindsight, the kinematics and mechanics of the damage was not clear at all to the various experts that visited the bridge. No much could be found of the previous studies carried out in '70 and on top of this, the mechanics of the new damages seemed to differ from the previous ones since wide new cracks were opening while previous damages could not be detected. The cause of the damage is obviously the slope instability, but the effect of this movement onto the structure was not clear enough. The cracks and displacements were so big that it was decided to start taking topographic surveys of the structure every month. These readings turned out to be extremely useful.

3.1 Numerical simulation

A 3D finite element model of the bridge was set up [4]. In order to keep the size within acceptable limit, only the arcades on the right bank and the main arcade over the Rhumel have been modelled. The effect of the rest of the bridge (the other 18 arches on the left bank) was accounted with boundary (spring) elements.

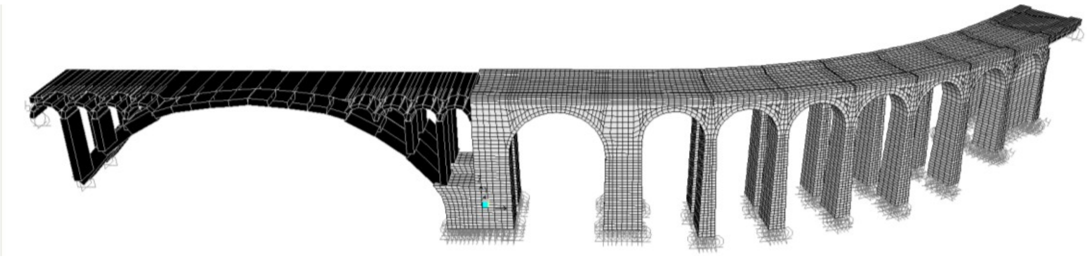

Fig. 4: The Finite Element Model of the bridge right bank and main arcades

The first 7 arcades, those were damage was taking place, were modelled using brick elements, the main arcade with beam elements. Given the necessity to quickly grasp the mechanics of the damage, a linear elastic model was used with iterative element elimination upon trespassing of tensile resistance (0.1 MPa) and compressive one (8 MPa). With only 3 iterations the kinematics of the damage mechanisms was immediately clear. These approach spans are in curve, actually quite a narrow curve (105 metre radius). When a push is applied from the abutment but also from the shear wall that was built between the first 4 piers (2 alignments), the bridge buckle and sway outwards. Very wide flexural cracks forms at the pier bases. All this was confirmed by the topographic readings, the outward sway of the deck is 20cm circa. Crack opening at the pier base up to 20mm, 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.

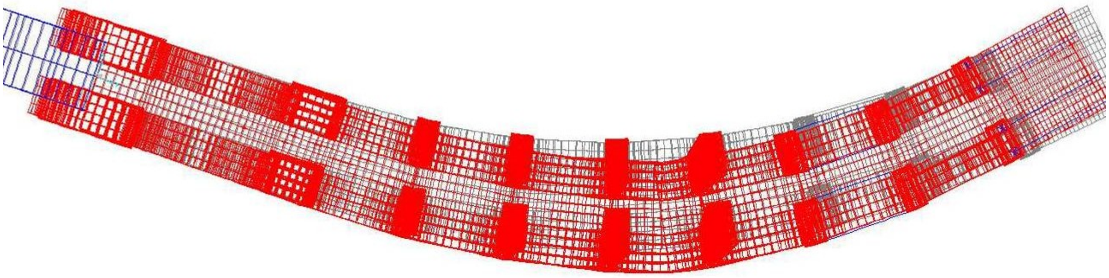

Fig. 5: The Finite Element Simulation. Amplified kinematics of the bridge deformation

Various failure scenarios were therefore examined. Although very large, the sway of the deck could not cause collapse by triggering P-D effects. Also the crushed arch between Pier 4 and 5, although severely damaged, has been hold in place by erecting provisional supports (scaffoldings) from the ground. The numerical simulations clearly identified the brittle failure of the piers as the most critical scenario. Rotations at the piers 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 following months by splitting cracks developing in the stone facing of 4 piers, those where the kinematics of the bridge imposed the largest rotations at the base sections.

3.2 The kinematics: topographic readings

Given the size of the flexural cracks at the pier base, it was decided to start collecting high precision topographic reading of the bridge on a monthly base. This type of survey could take advantage of the limestone rocks surfacing close to the bridge and thus providing reliable reference points for the triangulations. Readings were taken at the four corners of each pier for the base section and arch set one. The reading fully confirmed the results of the numerical simulations. With reference to the arch set ones shown in Fig. 8, we notice the following. The tangential (downhill) displacements are larger at the abutment and quickly decrease with the surfacing limestone (around Pier 4, as shown in Fig. 2). Radial displacement are very high for Pier 3 to 6 where the deck has swayed outward because of the planimetric radius of the bridge. Vertical displacements of the pier founded on limestone confirmed the pier rocking with vertical displacements proportional to the radial ones time the aspect ratio of the pier (rigid rocking of the masonry section).

The time evolution of these displacement are also very interesting. After the removal of the old buffer deck (summer 2011) the bridge started to slowly set back although restrained by the shear walls between Pier 1 and 2. Consequently small reduction in the radial outward sway was observed although the tangential (downhill) ones were still creeping during fall and winter 2011-12 because land slide was still active and progressive crushing of the arcade between Pier 4 and 5 possibly still ongoing. Last reading taken in summer 2012 shows a small increase of the radial displacement of the deck. This alarming inversion is very likely caused by the progressive damage at pier base sections, possibly facilitated by the inevitable vibrations caused by the micropiles and soil anchors borings currently being carried out to anchor the pier foundations to the limestone.

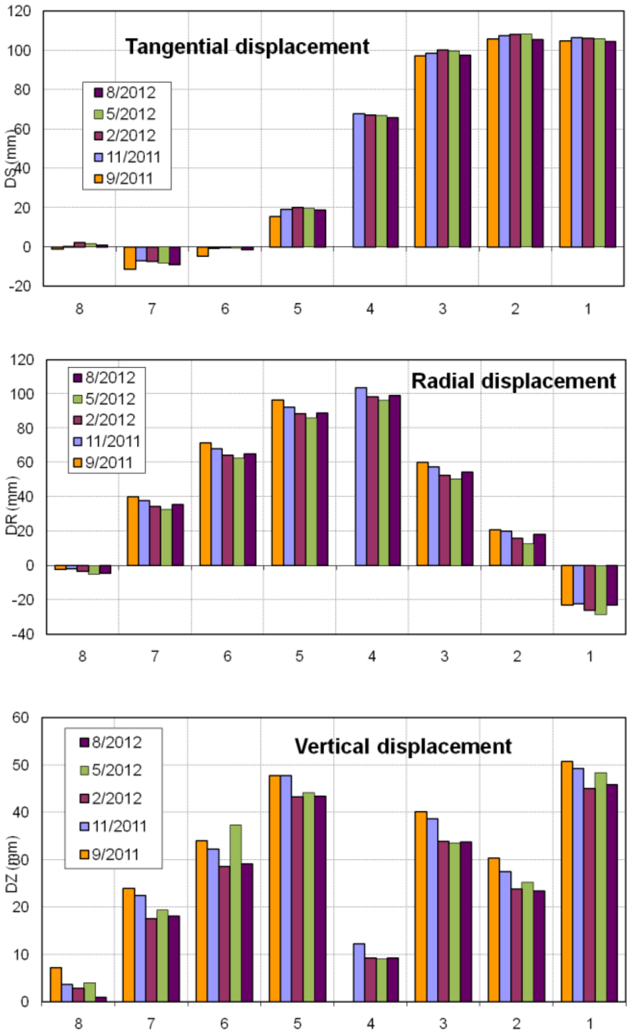

Fig. 6: Pier displacements at the arch set

4 THE REPAIR WORKS

The repair works have been phased so as to address the short and long term propping and rehabilitation needs of the structure but also those of the city traffic. Given the size of the landslide no quick fix can be found and therefore repair works on the bridge will have to adjust to the timing required for the slope stabilization. Unfortunately, there is no guarantee that the latter can be achieved before the bridge is completely wrecked. The Constantine's Public Work Authority dismissed an early proposal to demolish the last few spans of the bridge and replace them with a new structure capable of withstanding, absorbing or avoiding the downhill slide of that part of the slope. This was a bold decision, driven by cultural and heritage concerns but certainly very risky under a structural point of view.

4.1 Emergency propping and strengthening

The first interventions have been the temporary propping of the crushed arcade in order to allow the transit of pedestrian and cars on the bridge. Second intervention, in summer 2011, has been 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 differential displacement of the abutment. Unfortunately, during fall and winter 2011-12 the slope sliding peaked again requiring other two arcades to be propped and the most damaged piers reinforced with steel profiles and transverse prestressing so as to prevent their collapse.

Fig. 7 – Fig. 8: The Buffer deck between the abutment and Pier 1 and emergency propping and pier jacketing with steel profiles and external posttensioning

4.2 Foundation strengthening

Trying to alt a slope from sliding downhill with rigid retaining structures capable of absorbing the push is very often ineffective, especially in the long run, as happened for the works carried out on the bridge in the '70. Given the speed of the slope sliding something had to be done though, before it was too late. A series of inclined micropiles and soil anchors have been bored in between the piers so as to try to halt the 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 will prove successful, together with the complete kinematic decoupling of the abutment, they should prevent further deformation of the bridge.

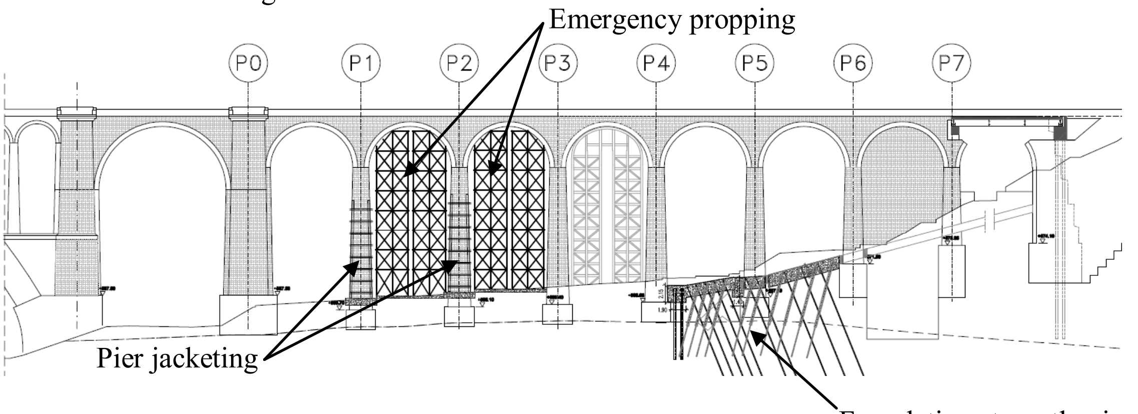

Fig. 9: The repairs works already achieved

4.3 Drainages and slope stabilization

Halting the abutment from sliding downhill with soil anchors was deemed unfeasible. The abutment seats on 15 metres of pélites, that are sliding onto the underneath limestone. In this part of the slope, stabilization will be hopefully achieved by coupling drainages with a stiff retaining structure. This structure will consist of two pits made with large diameter bored pile driven into the limestone. The two pits will be connected by a trench. This structure will provide the working space for boring sub-horizontal drainages into the pelites but it will be also capable of slowing down the slope sliding while disconnecting the uphill part of the slope from the downhill one so as to avoid the land slide to reach the rest of the bridge.

4.4 Reconstruction work

Once the soil instability will be tackled and the bridge will show no sign of further deformation, the collapsed arch between Pier 4 and 5 will have to be demolished and reconstructed. At that time, studies shall evaluate the possibility of inserting another buffer deck so as to allow for future soil sliding without introducing forces into the bridge. The interesting and critical aspect of this phase of the work is that, based on the numerical analyses, the bridge is still carrying a compression force in the deck of 900 tons. 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 Pier 1 and Pier 2 prevented the structure to set back. Demolishing the arcade between Pier 4 and 5 will release the axial compression in the deck and the bridge will set back and recover from the swayed and rocked position. A very delicate operation to perform, because it affect the static on the main arch over the Rhumel canyon.

5 CONCLUSIONS

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

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