Rescuing the Sidi Rached Bridge

Marco PETRANGELI
Professor
D'Annunzio University
Pescara, ITALY
marco@integer.it

Marco Petrangeli, born 1965, received his civil engineering degree from the Univ. of Rome. His main area of research is computational mechanics and bridge design.

Massimo PIETRANTONI
Geologist, Civil Engineer
Integra
Rome, ITALY
geo@integer.it

Massimo Pietrantoni, born 1963, received his geologist and civil engineering degrees both from the Univ. of Rome. His main area of activity is applied geology, slope stability and foundations.

Summary

The Sidi Rached Bridge, built in the early 20th century, crosses the deep Rhumel canyon in the centre of Constantine, Algeria. The bridge is made of 27 arches, with spans varying from 12 to the 68 metre of the main arch crossing the Rhumel 102 metres above the riverbed. The bridge is a famous city landmark and one of the main cultural heritage of Algeria as well as the largest masonry structure of this type in Africa. The 8 spans on the right bank have been suffering for over 50 years, from 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 spiked and 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 landslide 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 has therefore been undertaken. Using high precision topographic readings and 3D finite element model of the bridge the mechanics of what is taking place in the structure has been fully understood. Certainly more difficult will be the attempt to prevent the slope and pier foundations to keep on sliding. The paper presents the results of the study and the first interventions taken while monitoring, studies and works proceed on this historical monument that still provides a vital crossing in the hearth to one of the most populous cities of North Africa.

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

1. Introduction

The Sidi Rached Bridge, built between 1907 and 1912, 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 metres above the bottom of the Rhumel canyon, the Sidi Rached Bridge is still vital to the everyday life of Constantine and its citizens who use this bridge to cross the deep canyon cut by the Rhumel river right in the city centre.

The bridge is one of a particularly valuable lot of historic and very high structures crossing the Rhumel that granted Constantine the nick name of the "City of Bridges". The other three are two suspension bridges [2] and a concrete arch, all of them built in the early 20th century and still in service after 100 years despite a dramatic increase in axel loads and frequency.

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 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 to the first 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 4 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 4*2 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 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 being a 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 limestones, widely exposed in layers of various thickness 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 limestones 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 argillites, shales 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 limestones (see Fig. 2). 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 limestones 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.

The first signs of slope instability have been reported since the bridge construction although they did not cause immediate disruption to the structure. The effect of pore pressure combined with a low residual friction angle in the superficial clayey soils, has been recognised as the main cause of the instability and for this reason, drainage interventions has been put in place right after construction.

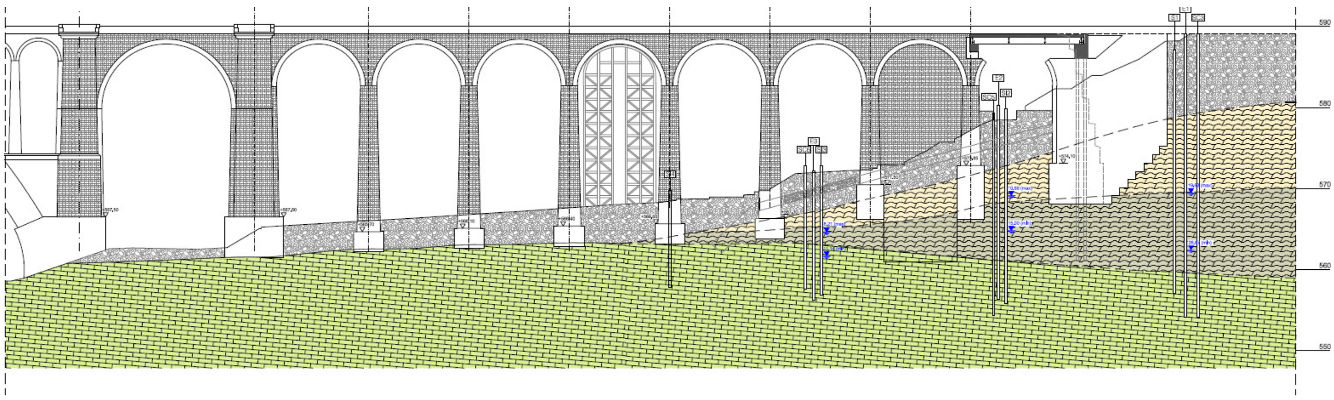

Fig.2 : Geological section of the right side of the Sidi Rached bridge

After many years of studies and investigations, mechanism and geometry of the landslide are not still completely defined. This is partly due to the lack of a regular monitoring, partly to the own characteristics of the phenomenon. Surveys have not found the basic features, as scarps and cracks, which can help to exactly define the extension of the landslide.

Depth of sliding is also not fully understood, but inclinometric measures, started regularly only during the last year, show a thickness of the mass affected by movements that rapidly decreases from approximately 30 m uphill the abutment to few metres around the 3rd and 4th piers. A direct relation between velocity/rate of the slide and piezometric levels could not be demonstrated yet although it is quite reasonable to assume a direct influence of it on the slope stability.

2.2 Damages and repairs; a brief history

Although slope instability was known from the construction time, serious damages developed 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 for the abutment to slide without pushing against the rest of the viaduct. The firs 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.

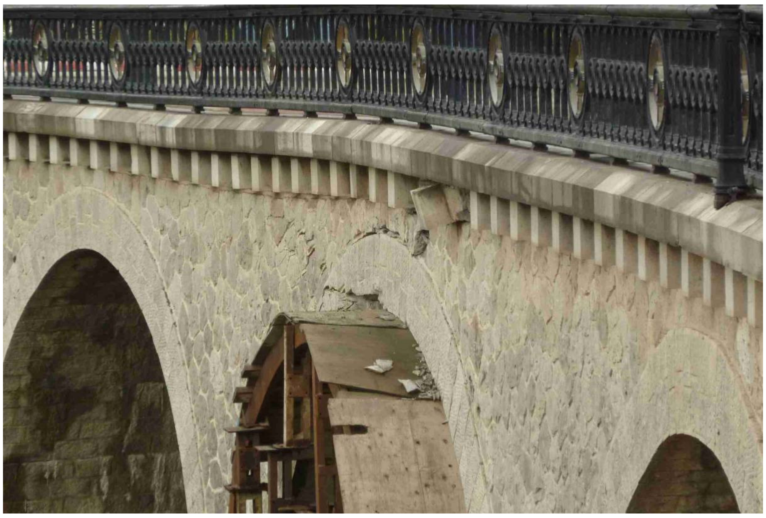

Fig. 3 : Crushing of the arch between Pier 4 and 5

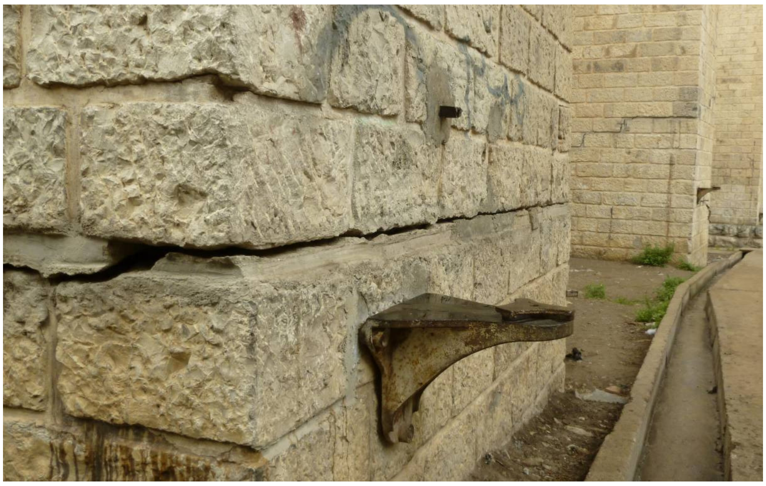

Fig. 4 : Wide flexural cracks at piers bases

Why these remedies did not last longer? A number of factors 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.

3. The numerical simulations

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.

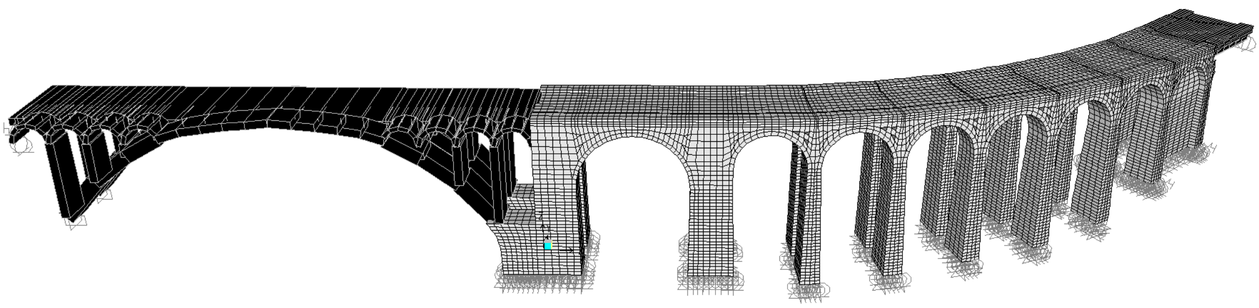

Fig.5 : The Finite Element model of the bridge right bank and main arcades

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. 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.

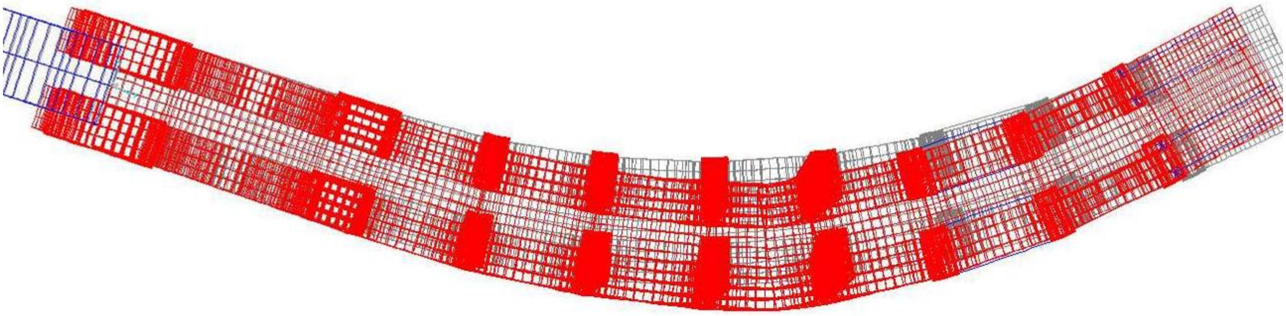

Fig.6: Finite Element simulation. Amplified kinematics of the bridge deformation.

3.1 Failure mechanisms

Fig. 7 : Splitting cracks in the piers

The possible failure scenarios had to be identified so as to carefully evaluate the possibility of keeping the bridge opened for pedestrian and light vehicles during the repair work. In other situations the bridge would be immediately closed and the surrounding area evacuated but in this case, closing of the bridge would completely disrupt the circulation ad everyday life of Constantine, a city of 2 million people. As a matter of fact, the main hazard was not that of the bridge users but that of the few hundred people living below and beside the bridge. Relocating these people and fencing off all the area below and beside the bridge right in the city centre was obviously quite unfeasible.

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 in a very advanced state, was tackled by erecting provisional supports (scaffoldings) from the ground. But the worst scenario, that of a brittle failure of the structure was easily identified from the numerical simulations and onsite inspections. Rotations at the piers bases were so high that the compression zone of these sections were very thin and subjected to very high stress, close to stone crushing, due to the bridge self weight. As a matter of fact, splitting cracks appeared in the following months in 4 piers, those where the kinematics of the bridge imposed the largest rotations at the base sections.

3.2 The kinematics: topographic readings

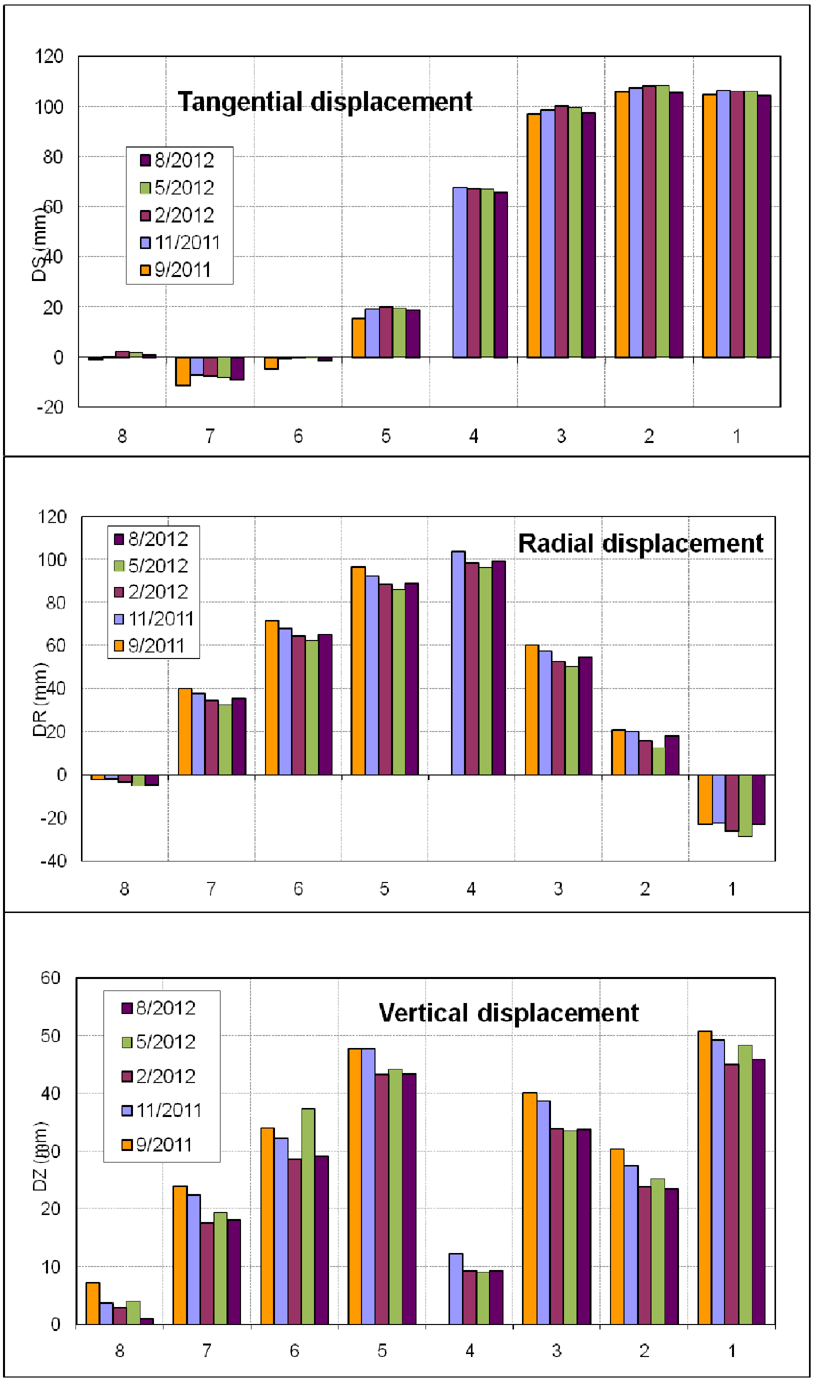

Fig. 8 : Pier displacements at the arch set

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.

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 arch in order to allow the transit of 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 for 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. 9 : The buffer deck between the abutment and Pier 1

Fig. 10 : Emergency propping and pier jacketing with steel profiles and external postensioning

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 are being bored in between the piers so as to try to halt the sliding of these foundations. The main drawback of these works are the vibrations generated by boring into the limestone for anchoring micropiles and anchors. If these interventions will be successful, together with the complete kinematic decoupling of the abutment, they should prevent further deformation of the bridge.

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 pelites 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, in case there won't be total confidence on the effectiveness and durability of the slope stabilization interventions, another buffer deck can be used so as to allow future soil sliding to develop 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 has not decreased 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 that arch while unloding the bridge that twill set back and recover from the swayed and rocked position will be a very delicate operation to perform.

5. Conclusions

Stone and masonry arch bridges are particularly vulnerable to soil instability and differential settlements. These structures, especially if important part of the national historical and architectural heritage as the Sidi Rached, should be continuously monitored so as to be ready to undertake the necessary measures in due time. Soil instabilities such as the large big land slides 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 this instabilities are halted and their cause removed.

6. Acknowledgements

The authors would like to acknowledge the fruitful partnership with SAPTA, the Algerian construction company which is in charge of the repair work and the whole technical staff of Constantine's DTP (Direction Travaux Public) for the reciprocal trust and esteem in dealing with such a delicate issue. The authors would also like to tank Rashid Bayasly, CEO of SAPTA and Ammar Remmache, Director of the DTP for their friendship, understanding and personal contribution to the project.

References

[1] DELBEQ JM, "Les ponts en maçonnerie. Historique et Constitution", SETRA, Bagneux, France.

[2] PETRANGELI M., and PETRANGELI M., "Rehabilitation of the Cidi M'Cid Suspension Bridge, Algeria", *SEI*, No. 4, 2000, pp. 254-258.

[3] BENAISSA A. and BELLOUCHE MA., "Propriétés géotechniques de quelques formations géologiques propices aux glissements de terrains dans l'agglomération de Constantine", Bulletin of Engineering Geology and the Environment. Vol. 57 – N3 – March 1999.

[4] LOURENCO P.B., "Experimental and numerical issues in the modelling of the mechanical behaviour of masonry" *Structural analysis of historical constructions II, CIMNE*, Barcelona 1998