Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Geotechnical measures for stabilization of the Aqueduct in Skopje

Mesures géotechniques pour la stabilisation de l'aqueduc de Skopje

Jovan Br. Papić, Igor Peševski & Radica Jovanova
Ss. Cyril and Methodius University in Skopje, Faculty of Civil Engineering, R. N. Macedonia, papic@gf.ukim.edu.mk

Atanas Strašeski
GEING, Skopje, R. N. Macedonia

ABSTRACT: One of the last remaining aqueducts on the Balkan Peninsula is located in Skopje, the capital of R. N. Macedonia. It is about 400 m long and 6 m high. Unfortunately, it has suffered destruction both from geotechnical, earthquake and vandalism reasons, while recently two inclinations have appeared: both are about 50 cm in size and at lengths of approximately 25 m. In order to determine the reasons for such damages, both historical and existing technical documents were reviewed, since some activities were realized several years ago. However, additional geotechnical investigations and tests were performed. It was found that there are very heterogeneous soil conditions beneath and along the structure, including soils with high swelling capacity. In addition, the location itself is swampy and is a seismic prone area where, moreover, two faults were detected nearby. Thus, the project had to deal with all these elements and to supply permanent stabilization. Several different techniques were analyzed and compared from technical and economical aspect. The paper digests the performed field and laboratory tests, the numerical analyses modelling, the difficult conditions and the behaviour of the aqueduct, and presents the geotechnical measures to restore it.

RÉSUMÉ: Un des derniers aqueducs qui reste à la péninsule des Balkans est situé à Skopje. La longueur de l'aqueduc est d'environ 400 m et la hauteur est 6 m. Malheureusement, il a souffert des destructions pour des raisons géotechniques, sismiques et de vandalisme, Entre-temps, récemment deux inclinaisons sont apparues: les deux ont une taille d'environ 50 cm et longueur d'environ 25 m. Afin de déterminer les raisons de ces dommages, des documents techniques historiques et existants ont été examinés, car certaines activités ont été réalisées il y a quelques années. Des investigations et des tests géotechniques supplémentaires ont été réalisés. Il a été constaté qu'il existe des conditions du sol très hétérogènes en-dessous et suivant la longueur, notamment le sol à grande capacité de gonflement. Par conséquent, l'emplacement lui-même est marécageux et est une zone sismique exposée où, en outre, deux failles tectoniques ont été détectées à proximité. Ainsi, le projet devait faire face à tous ces éléments et fournir une stabilisation permanente. Plusieurs techniques différentes ont été analysées et comparées d'un point de vue technique et économique. Le papier digère les essais de terrain et de laboratoire effectués, du modelage numérique structurel et des analyses statistiques, les conditions difficiles et le comportement de l'aqueduc, et présente les mesures géotechniques pour le restaurer.

KEYWORDS: aqueduct, inclination, stabilization, swelling, micropiles.

1 INTRODUCTION

The Skopje aqueduct, located just 4 km from the central Skopje, is a monumental building of the type of "one-tier above-ground water supply systems" and it is preserved in its entire length of 385.80 m. It consists of 53 square or rectangular piers (S), with a centre-to-centre distance of 6.50-6.70 m, 2 lateral ramps, 54 arches, walls above the arches, cornices and water supply structure. There are several presumptions about the Aqueduct's dating, since it is still not finally determined: that it had been built in Justinian's time (6th century) or that it originates from the 15th or the 16th century. Because of the great importance of the Aqueduct, for not only the history, culture, art and science in our country, but in the much wider region, it is a subject of interest of international professional and scientific public. Therefore, a procedure has been initiated for its preservation and rehabilitation. Namely, in the current situation, the Aqueduct in Skopje as a construction faces problems of a constructive nature, which affect its stability and further existence, as well as major damage to the architecture of various types.

This paper covers the conducted geotechnical activities and planned rehabilitation and stabilization of the foundation structures, in order to prevent rotation of certain piers.

2 CURRENT CONDITION OF THE STRUCTURE

Although the Aqueduct exists in all its length, its integral parts are not in the best condition, while some are preserved to some extent. The basic reason for that factual condition is the constant exposure to atmosphere and the lack of measures for maintenance and direct protection. Thus, the greatest challenge is found in a severe destructive transformation of some piers, arches and the entire construction above them and inclination from the vertical state.

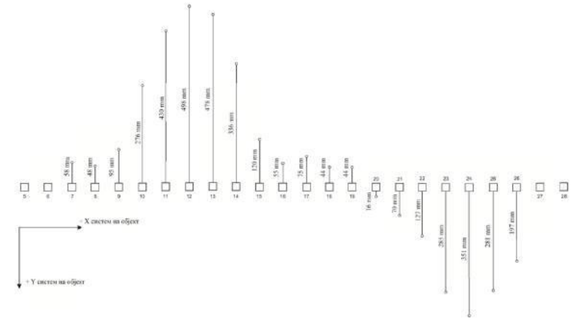

Figure 1. Maximum horizontal deformation of the piers (layout).

Vertical deviation to west was observed at piers S7 to S19, in values ranging from -44 mm for S18/S19 to -498 mm for S12.

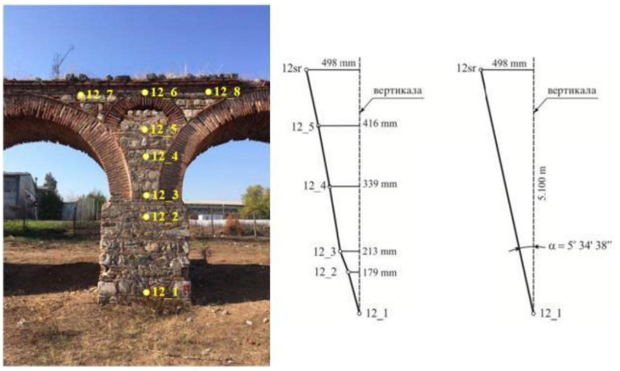

Figure 2. Inclination of Pier S12.

Vertical deviation to east was observed at piers S20 to S26, in values ranging from +16 mm for S20 to +351 mm for S24.

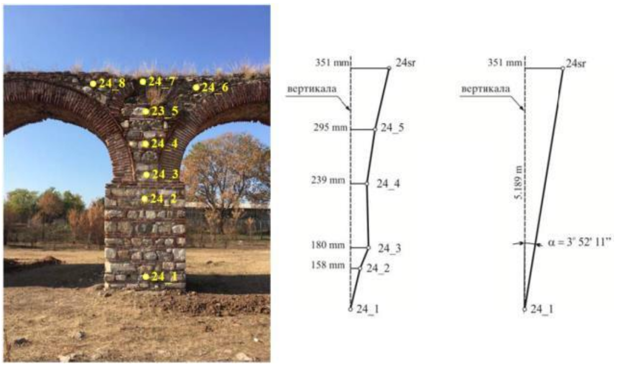

Figure 3. Inclination of Pier S24.

Foundation dimensions under the piers are equal to the piers above the ground, and there is no separate foundation structure. They are dug in the natural terrain and built of stone and mortar. This building method is applied to the ground elevation where the masonry of the surface part of the piers begins.

Pier foundations are of similar height, while the foundation depth varies around 1.0÷1.50 m, depending on the terrain configuration. The foundations bases are relatively square-shaped, 2.15 to 2.24 m wide. They are in good condition, without any visible damages, cracks or devastation of the substructure.

3 GEOTECHNICAL INVESTIGATION WORKS

Two investigation campaigns were carried out in order to collect geotechnical data along the entire length of the Aqueduct.

The first investigation in 2014 included performance of 10 boreholes, 8 wells, 8 CPTs, several SPTs and geophysical tests. Besides that, soil samples of the most common materials were taken from the boreholes, after which laboratory tests were performed. Interpretations and correlations revealed a heterogeneous terrain composition along and below the aqueduct and, as expected, quite various properties, with observed groundwater in some locations, although at greater depths.

Investigations were updated in 2019, with additional investigative works in the area of endangered piers on the layer on which the most of the building is founded, located near the surface: CI/MI. Although with a relatively lesser thickness, its properties are important as it participates in receiving the largest loads, and therefore the largest deformations begin here. At the same time, in order to determine the condition of the structure at the pier-foundation contact (foundation depth, pier inclination, contact shear, cracks in materials, etc.), trenches were performed at corners of piers 12 and 24. The excavated material was used in several laboratory tests.

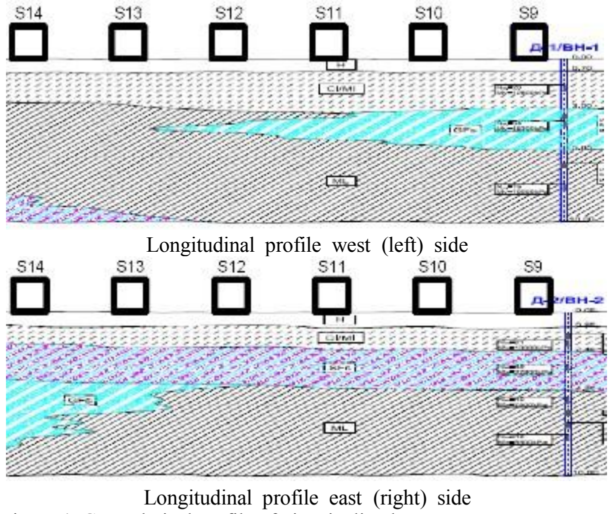

Figure 4. Geotechnical profile of piers inclined to west.

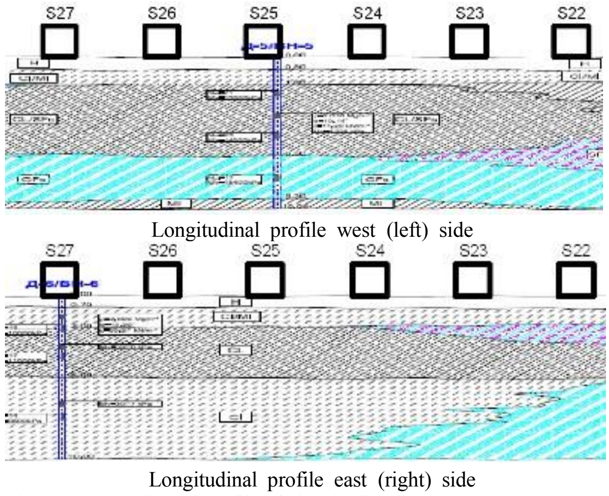

Figure 5. Geotechnical profile of piers inclined to east.

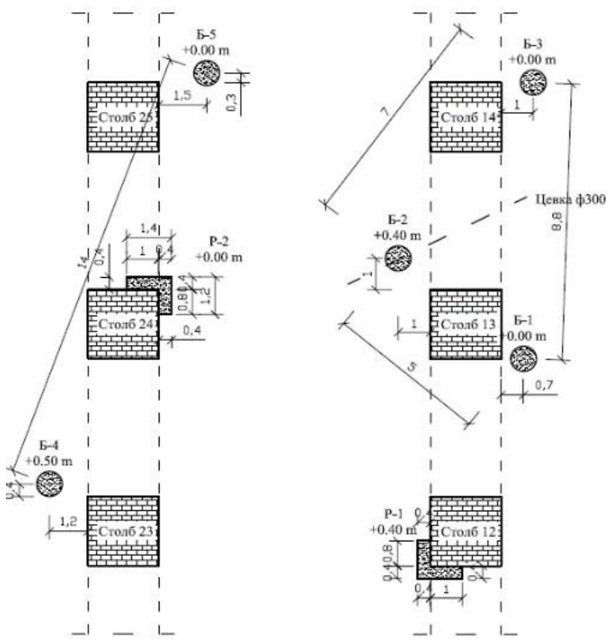

Figure 6. Additional geotechnical works (wells and trenches) conducted in 2019 in vicinity of the most inclined piers: for piers 23-25 (left) and for piers 12-14 (right).

4 POSSIBLE CAUSES OF PIERS INCLINATION

Analyzing all the data collected during investigation campaigns, including not only the geotechnical but also the archaeological and conservation works, it is not possible to define the period of realization of deformations or the beginning of the process of their realization, nor the reasons that led to pier inclinations. However, some data point to possible causes.

4.1 *Anthropogenic influences*

Anthropogenic influence certainly has a share in the realization of deformations or at least in allowing another series of events to lead to the current state.

At first, some parts of the aqueduct site were used as landfills for construction waste, especially after the strong earthquake of 1963, which changed the morphology. The aqueduct axis is cut by an artificially formed canal for the river Serava, which in the past did not pass through this area, thus affecting the natural flow of surface and groundwater. That leads to continuous water saturation of the terrain.

On the other hand, the formation of a concrete canal and the uncontrolled deposition of construction waste caused the formation of higher zones that are drained naturally and concave zones that cannot drain in such way. Hence, the water is retained during the rainy periods and the groundwater level is rising in the lowest parts, right near the endangered piers, which also endangers the foundations of the monument.

Certainly, the presence of some other influences for which there is no evidence or evidence cannot be provided cannot be excluded.

4.2 *Geotechnical conditions*

Not all these reasons would have any adverse effect if they were not followed by other preconditions.

Therefore, the possible causes or preconditions from a geotechnical point of view can be found in the local tectonics and alterations in the spreading of the surface clay layer, the effects of clay swelling, and the rather weak deformability properties of clay and the shallow structure foundation.

Additional investigative works suggest that the insufficient bearing capacity and the changes in physical and mechanical characteristics of the clay, depending on the presence of water and the effects of the clay swelling, are one of the main causes of deformations of the aqueduct piers.

What is particularly striking is the relatively high swelling pressure that occurs in clay at the foundation level.

5 STABILIZATION MEASURES

The basic concept of stabilization measures consists of reducing and preventing any further uncontrolled inclination of the piers, namely S10-S14 and S22-S26 (10 piers in total).

First, it should be emphasized that given the measured values of the piers inclinations, especially of the most critical piers S12 and S24, the force of a dead weight still falls within the zone of the section core, i.e. the eccentricity does not lead to occurrence of tension zones at the foundation-soil contact. However, this situation can be easily overcome, since the current equilibrium state is assured in a complex way: partly through the contact stresses of the foundation with the soil, but also with additional assistance of the adjacent piers through the arches, in which a change in the state of stresses is probably realized. Any further impacts, on the one hand – additional damage to the arches and piers, on the other hand – changes in the geotechnical condition, and, thirdly – dynamic external impacts and seismic, can easily exceed the established equilibrium which is considered unstable and may lead to progressive deformations that will end in a total failure of the considered piers.

5.1 *Direct stabilization measures – micropiles foundation*

Focusing on the problem of inclination in the pier foundation layer, as the main cause, the proposed technical solution consists of applying deep foundation using a micropile technology. They will serve as deep foundation elements loaded with compressive force, but also as anchor structures loaded with pullout forces.

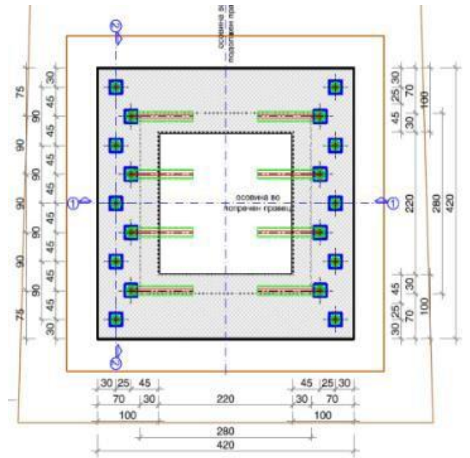

Figure 7. Plan view of pier and micropiles.

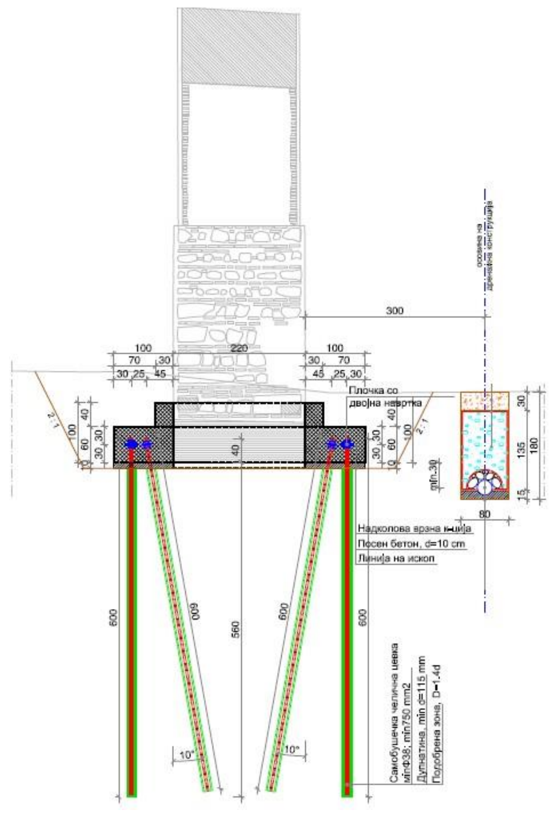

Figure 8. Cross-section of pier and micropiles.

In addition to this direct effect, they also have indirect influences on improving the overall conditions, since they improve the strength-strain state of the soil immediately under the piers and enable better interaction between the structure and the soil medium. On the other hand, such an integral complex of the structure – with inclusion of the soil medium affected by the micropiles – leads to significantly larger dimensions in the lower zone, unlike the current state with rather shallow foundation depth. Therefore, the centroid of the integral structure is placed to significantly lower position, thus directly affecting the seismic resistance and the stability against overturning.

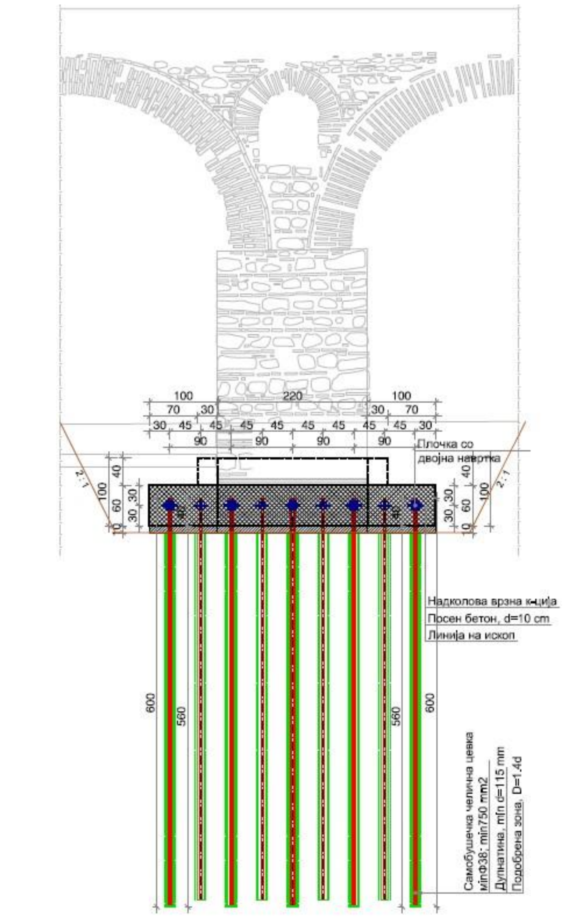

Figure 9. Longitudinal section of aqueduct and micropiles.

Eighteen micropiles were designed under each pier with a diameter of min Φ115 mm and a length of 6.0 m, set in four rows: two rows on both sides of the aqueduct axis. The outer two rows (position I and position IV) are designed as vertical at a distance of 0.70 m from the outer side of the piers, while the inner two rows (position II and position III) are designed inwardly inclined at an angle of 10˚ of the vertical, 0.50 m from the outer side of the piers. The centre-to-centre distance between micropiles in one row is 0.90 m, and 0.20 cm between the two rows. Micropiles in both rows on one side are placed in a zigzag pattern, with 5 micropiles provided for positions I and IV, and 4 micropiles for positions II and III.

Micropiles are connected by L-shaped pile cap structure. Its lower part is 1.0 m wide and 0.60 m high, while the upper part is 0.30 m wide and 0.40 m high. In addition, this structure serves for surrounding the aqueduct piers, as it is placed along their entire perimeter, enabling cooperation with micropiles that are performed only on two sides, along the aqueduct. The surface of the piers and their foundations is significantly rough, which enables a larger friction at a contact with the designed structure.

5.2 *Indirect stabilization measures – drainage*

The observed long-lasting retention of surface water next to the aqueduct piers during the year requires preparation of drainage measures for this area. In order to intake and run-off the infiltrated groundwater and drain the retained surface water, a drainage trench is designed on the east (right) side of the aqueduct in a depth to max. 2.50 m. Actually, it is set below the level of piers foundation, and the intake water is discharged into the riverbed of Serava. This measure would prevent any further adverse effects of the water on the soil layer used for pier foundation, including the swelling, which will affect not only the repaired, but also all other piers.

6 ANALYSIS

6.1 *Analysis model*

Due to the complexity of the site conditions in the aqueduct zone, two independent models have been developed to interpret the behaviour of the soil half-space, i.e. the interaction between the soil and the piers. They are implemented for piers with the highest levels of deformations in opposite directions, pier 12 and pier 24. The analyses of the stress-strain state of the piers, as well as the soil half-space around the structure, are performed in the software package PLAXIS.

6.1.1 *Geotechnical profile*

Based on the geotechnical investigation works, micro location profiles of the two analyzed piers were prepared.

Table 1. Adopted geotechnical parameters.

Material	γ [kN/m^3]	E_{oed} [MPa]	c_{ref} [kPa]	φ [°]
H	18.50	3.00	12.00	10.00
CI/MI	19.50	12.00	10.00	15.00
SFs(S12)	20.00	28.00	10.00	19.50
CL/SFs, CL(S24)	20.50	12.50	23.00	19.50
CI(S24)	19.50	9.50	15.00	15.00
GFs	21.50	32.00	3.00	33.00
ML	18.50	14.50	12.00	17.00
Aqueduct	27.50	1200.00	/	/

All soil materials are defined according to the drained Mohr-Coulomb material model. Additionally, the aqueduct is modelled using a soil bulk model, but with application of a linear-elastic soil model, since the internal state of stress of the aqueduct is not subject to analysis, but only its actual geometry and loads it transfers to the ground. The three-dimensional effect is taken into account when determining the volume weight, i.e., the corresponding load from the arches, as well as the values of the volume weights of materials used for the aqueduct construction.

6.1.2 *Structural elements*

Micropiles rows in a cross section are modelled with an elastic plate element, and due to their discontinuity with this element, the condition for equivalent stiffness is observed according to the moments of inertia of cross sections as well as the corresponding surfaces of one structural element. Reinforced concrete pile cap structures are also modelled with plate elements.

Table 2. Parameters of structural elements.

Element	EA [kN/m]	EI [kNm^2/m]	ν [/]	w [kN/m/m]
Micropiles	3.58×10^5	2.96×10^2	0.15	0.28
Pile cap	1.89×10^7	5.67×10^5	0.15	15.00
Vertical plate	9.45×10^6	7.09×10^4	0.15	7.50

6.2 *Analysis procedure*

The software simulation of technical solution is performed in several successive stages. First, the model was calibrated, and then the remedial measures were applied to such calibrated model, after which they were analyzed for different impacts:

Model A – Current state
- Stage A1 – Initial stage;
- Stage A2 – Aqueduct construction;
- Stage A3 – Model calibration;

Model B – Stabilization measures
- Stage B1 – Initial stage;
- Stage B2 – Aqueduct construction;
- Stage B3 – Remedial measures;
- Stage B4 – Swelling load – Load case 1 (LC-1);
- Stage B5 – Swelling load – Load case 2 (LC-2);
- Stage B6 – Seismic load – Load case 3 (LC-3);

6.2.1 *Current state – calibration model*

The analysis of the current state is in fact a back analysis with application of calibration in order to determine the strength-strain parameters of the soil layers as well as other conditions that led to the current state of the structure, especially the analyzed piers.

The current state is possibly a result of superposition of several listed influences, so a comprehensive numerical model of analysis has been prepared, in accordance with the actual site conditions. However, in order to simplify the analysis, the common engineering practice suggests calibration of the current state through one of the dominant causes.

In this particular case, the swelling of the clay used for piers foundations is adopted as the dominant cause; according to geomechanics investigation works, its value is rather high, up to 400 kPa.

The swelling is modelled by applying a load under the piers foundations in an upward direction. In addition, in order to achieve the current rotation of piers, it is adopted that this load acts on 1/4 (55 cm) of the foundation base. The intensity of this load is calibrated in order to determine the current piers deformations. Hence, it is determined as a trapezoidal load with a value of 338-400 kPa for pier 12 and 392-400 kPa for S24.

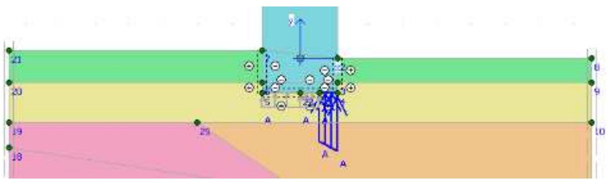

Figure 10. Calibration load – Pier 12.

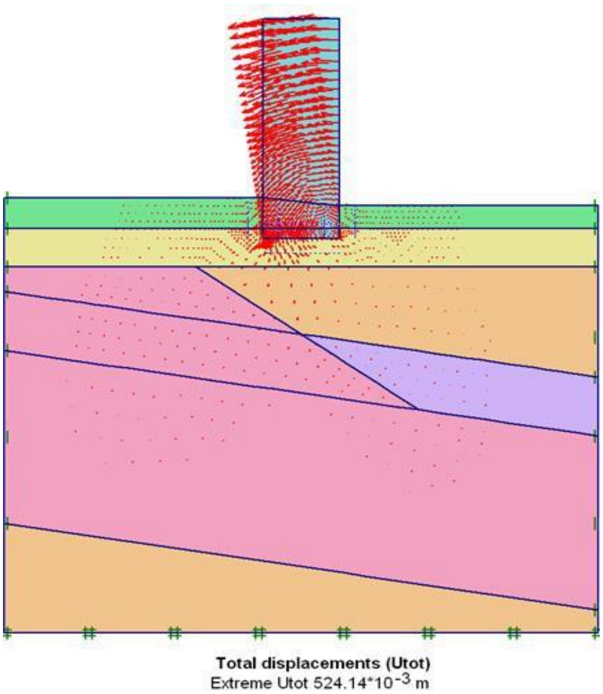

Figure 11. Total displacement of calibrated model – Pier 12.

6.2.2 *Stabilization measures – Load case 1 (LC-1)*

An entirely new model with remedial measures included was prepared in order to carry out the required analyses. Since this is a remediation, in most cases the most justified solution (in favour of safety) is that – before applying the critical case/load that led to ground deformations – to apply the remedial measures and to analyze them for the critical case/load. In fact, this is a fictitious state which would actually imply that the remedial measures were performed before the occurrence of deformations. Such a structure was loaded for a state in which the current realized deformations occurred, i.e., in LC-1 the swelling load – as determined by the analysis in the calibration model – is applied on part of the existing (current) foundation base.

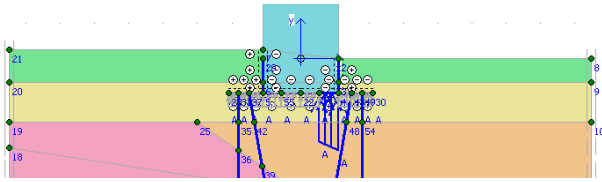

Figure 12. Load case 1 – Pier 12.

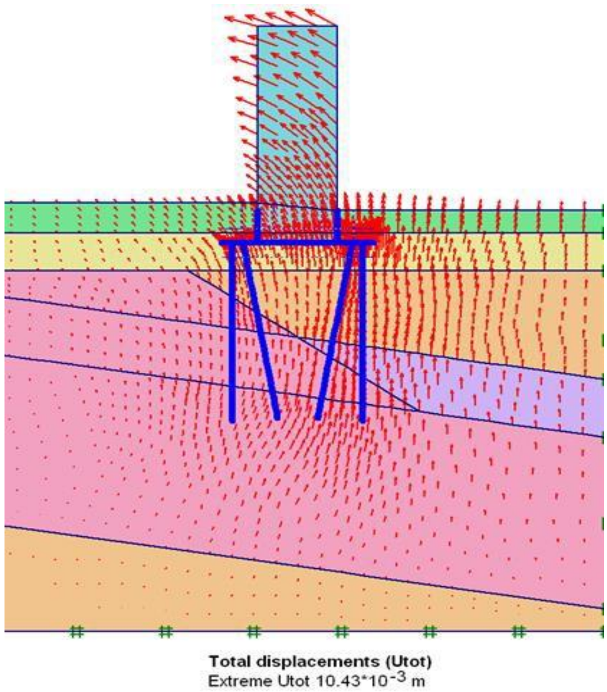

Figure 13. Total displacement LC 1 – Pier 12.

6.2.3 *Stabilization measures – Load case 2 (LC-2)*

Load case 2 is actually a newly created state where a swelling load may occur under the recently built structural elements, i.e. under the L-shaped pile cap. In fact, the remediation elements would prevent the possibility of swelling under the existing pier foundation (water infiltration to the existing foundation), i.e., the infiltration would be realized only under the widening of the foundations and swelling would be realized there.

In addition, in order to achieve the most unfavourable state, it is adopted that this load acts at 55 cm from the edge of the base of the extended foundation. The intensity of this load is predicted to be 400 kPa, which is actually the maximum value tested in the additional investigative works.

6.2.4 *Stabilization measures – Load case 3 (LC-3)*

Load case 3 is the recently created state where the swelling pressure under the existing foundations is taken into consideration, as described in Load case 1.

In addition, this state is loaded with pseudo-static seismic loads. The seismic impact is modelled through horizontal and vertical seismic acceleration coefficient. Namely, the location belongs to the area with a maximum intensity up to VIII and IX° according to MCS, which have been registered in the past in the Skopje region. So, for that purpose, seismic loads with seismic acceleration coefficients kh = 0.12 and kv = 0.06 are adopted.

6.3 *Analysis of results*

First, results of the analysis of the current state are presented, with a comparison of the measured site deformation values. Presented values are the maximum values along the vertical axis of the piers.

Those values indicate that the calibration, i.e. the equalization of the modelled with the actual deformations, was carried out with considerable precision, having in mind the geotechnical complexity of the problem.

Table 3. Measured and calibrated deformations.

	Pier 12		Pier 24	
	measured	calibrated	measured	calibrated
u [mm]	/	506.60	/	358.34
ux [mm]	-498.00	-503.07	351.00	352.37
uy [mm]	/	-59.71	/	-65.14

This is followed by presentation of results of the analysis for the structure after remedial measures as well as loading of the structure with several different load cases, as described above: LC-1, LC-2 and LC-3.

Presented values suggest that the planned technical solution fully meets the requirements, i.e. the designed deformations fall within the allowable limits for static and seismic loading of the structure.

Table 4. Calculated deformations for different load cases.

	Pier 12			Pier 24		
	LC-1	LC-2	LC-3	LC-1	LC-2	LC-3
u [mm]	9.81	24.07	33.37	10.96	22.71	40.66
ux [mm]	-8.95	-23.47	-31.91	7.20	21.07	38.42
uy [mm]	4.06	5.36	9.76	8.32	8.47	13.31

Dominant loads in the micropiles are the axial forces on compression and pullout.

The maximum axial forces in micropiles are: compression - 26.10 kN and tension 117.94 kN.

As described above, the micropile rows are marked with position I - position IV, which corresponds to the sequential arrangement of micropiles from west (left) to east (right).

Table 5. Calculated axial force in the micropiles [kN].

	Pier 12			Pier 24		
	LC-1	LC-2	LC-3	LC-1	LC-2	LC-3
I	14.29	-22.04	-18.97	65.12	**111.30**	**117.94**
II	-2.90	-26.10	3.85	33.12	51.17	39.39
III	31.17	47.75	35.68	2.60	-22.17	5.72
IV	54.45	**103.32**	**94.04**	11.97	-19.96	-21.86

7 CONCLUSIONS

The huge importance of the Skopje Aqueduct for the cultural heritage in R. N. Macedonia has imposed great responsibility in preparing the remediation design.

The long lifespan of the structure has caused it to be exposed to various influences and it is a great challenge to identify the reasons that led to its current state.

Several types of remedial measures were considered, among which some were not applicable due to different reasons. E.g., repeating of positions in close proximity of the Aqueduct during execution of concrete piles poses a great risk. So, the planned micropiles and drainage trench are a very elegant solution for stabilization of the rotated piers, since it does not take up significant space and, at the same time, does not disturb the visual appearance of the structure above the ground. It is technically justified from the aspect of meeting the stability requirements, overcoming the indicated causes of piers rotation. Additionally, the risk of its damage is minimized from the standing point of execution of works.

The Government of R. N. Macedonia has recently proclaimed the Skopje Aqueduct for a monument of exceptional importance, while the National Conservation Centre has – by the submission of the paper – approached towards realization of the presented stabilization solution with the coupled geotechnical measures.

8 REFERENCES

Faculty of Civil Engineering Skopje. 2019. Report on geotechnical laboratory tests for Aqueduct in Skopje.

Faculty of Civil Engineering Skopje. 2019. Technical solution for stabilization of inclined piers of the Aqueduct in Skopje.

Geing Krebs und Kiefer International Ltd. Skopje. 2014. Elaborate for geotechnical investigations and testing on the location Aqueduct in Skopje.

Građenje Ltd. East Sarajevo. 2014. Technical documentation for preparation of the executive design for conservation and restoration of the Aqueduct.