INTERNATIONAL CONFERENCE
OF APPLIED SCIENCES, ENGINEERING
AND MATHEMATICS (ICASEM 2021)
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ID # 49

Inclined Aqueduct of Skopje: A History in Brief and Preparation for the Future

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Abstract:

One of the last remaining aqueducts on the Balkan Peninsula is located in Skopje, the capital of R. N. Macedonia. It stretches approximately 400 m in length and is about 6 m tall. Unfortunately, it has suffered great destruction, and two inclinations have appeared which threat its existence. In order to determine the reasons, historical and existing technical documents were reviewed, geotechnical drillings were conducted and exhaustive laboratory tests and office works were performed. It was found that the soil layers are heterogeneous, part of which having a very high swelling capacity. Also, the location is swampy and there are two tectonic rifts just underneath the aqueduct. Thus, it was necessary to prepare a project which will deal with these elements in order to supply permanent stabilization. Several different techniques were analyzed and compared from both a technical and economical aspect: enlarging the shallow foundations, applying large size reinforced concrete piles or installing steel self-drilling micro-piles. The presentation will digest the performed field and laboratory tests and the complex numerical analyses modelling the behavior of the aqueduct under the influence of the local devastating earthquakes and difficult soils, respecting the already weakened material in the above structure.

Keywords: *Aqueduct; Inclination; Swelling; Stabilization; Micro-piles*

1. Introduction

Water supply used to be a great issue facing humanity. During the Ancient and Middle ages, one of the ways to solve this problem was with construction of aqueducts: these monumental structures, built of stone, brick and mortar, transferred fresh water from capable sources in higher locations to large cities. One of the last remaining aqueducts on the Balkan Peninsula, built during the Ottoman Empire, is located in Skopje, with length of nearly 400 m and height of about 6 m.

Figure 1 View on the Skopje Aqueduct

Unfortunately, it has suffered destructions, and recently two inclinations have appeared: towards east at one section long 25 m, and towards west at other section with similar length. Their size is up to 60 cm, i.e. 10% of the height, which is tremendous and is threatening the existence of the aqueduct. In order to determine the reasons for such damages, review of historical and existing technical documentation was realized, geotechnical drillings have been conducted at the location, above- and underground structure conditions were mapped, soil samples were taken for exhaustive laboratory tests and office works were performed for selection of appropriate stabilization measure. It has been found that there are very heterogeneous soil layers beneath and along the structure, part of which have swelling capacity high enough to lift up the aqueduct. This is appropriate for the upper layers, which are quaternary sediments – clay and silt, while the deeper ones consist of sand and gravel, which, together with the swampy location, leads to great differential settlements. Also, Skopje has regularly suffered from very strong earthquakes in the past and moreover: two tectonic rifts were detected just under the aqueduct! Not to leave behind, the human factor is also included: four of the columns were ruined and reconstructed later because of military exercises, while having been built in the time of the Ottoman Empire, gullible people thought it was a good idea to dig for gold, around, under and in the columns.

As the pillars are continued in the ground same as above, there is no specific foundation construction of the Aqueduct. This might be other reason for the damages, where the most alarming is the serious eccentricity that the columns are confronting: more than 0.5 m for few of them. As mentioned above, what demands special attention are the size and direction of the current inclinations: one group of columns are inclined towards west, among which the most inclined is column C13, for 53 cm, while among those inclined towards east the most endangered is column C26, with 22 cm. Other challenges are the flow of underground water, which has undermined the pillars, and the very bad actual construction of the above part of the pillars

Figure 2 *Devastation after military exercises*

Figure 3 *Human factor in destroying the pillars of the Aqueduct*

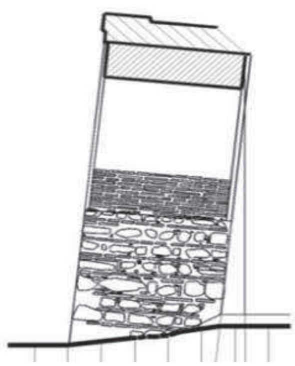

Figure 4 *Cross-section of inclined columns*

2. Numerical analyses

Thus, the project had to deal with these elements and to serve high quality, guaranteed and permanent stabilization. Several different techniques (enlarging the shallow foundations; applying large size reinforced concrete piles; installing steel self-drilling micro-piles) have been analyzed in software based on Finite Elements Method (FEM) modelling the behavior of the aqueduct (separately with each stabilization measure) under the influence of the local devastating earthquakes and difficult soils, respecting, of course, the already weakened material in the above structure, and compared from technical and economical aspect. The numerical analyses are described below.

2.1. Numerical modelling in ROBOT

Considering the fact that each column had to be analyzed separately due to complex geology, the analysis using the FEM Robot Structural Analysis Professional was demanding. This software provides advanced construction simulations and huge capacities for analysis of complex structures. This software is fast, efficient and easily customizable, and calculates complex models. For this structural model, the arches were modeled as panels, given the appropriate thickness, and stiffness coefficients were used for bearing supports, depending upon the compression modulus below each column. To provide a seismic analysis, the dynamic method was used, so pseudo-static forces were generated for each mode shape. Each of it has its own coefficient of participation in seismic calculation from the total mass of the structure, so quadratic combinations were applied.

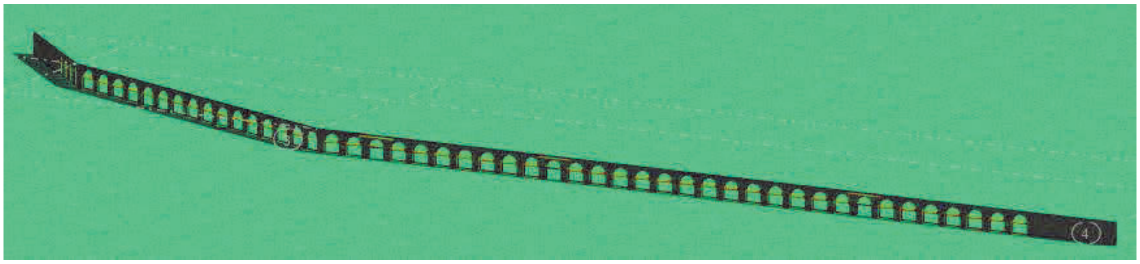

Figure 5 Longitudinal model of the Aqueduct in ROBOT

The results obtained were 2.1 cm maximum vertical deformation from the load case self-weight and when seismic was included, a maximum deformation (buckling) of 0.4 cm was reached (so called, CQC-double sum method).

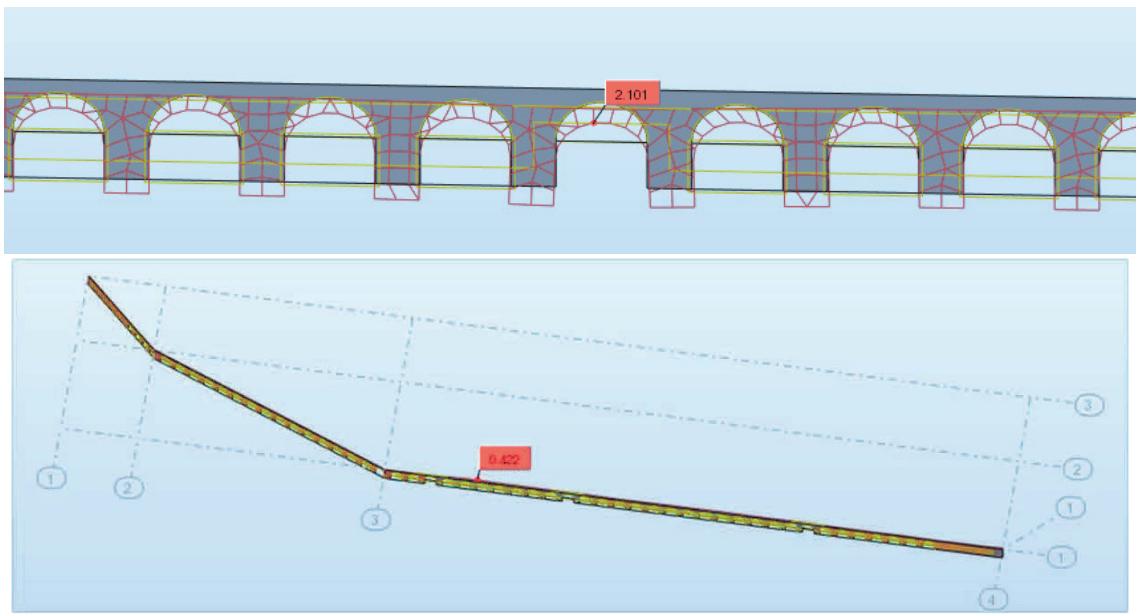

Figure 6 Findings from the modelling in ROBOT: vertical and horizontal deformations

This type of results, in some way, once again confirm the complexity of the problem and the mystery the past has left. This kind of software does not allow heterogeneous layers to be precisely modeled, but instead only stiffness coefficients are used below each column. Another important thing that is left behind is the swell capacity of soil, which proves that probably the seismic is not the main reason for the damage.

2.2. Numerical modelling in PLAXIS 2D

These lacks were overcome with the geotechnical FEM software PLAXIS 2D, which is used to analyze the deformations, stresses, and stability, while considering the non-linear and time-dependent behavior of soil, consolidation of soil, as well as ground water. For such purpose, several soil models were implemented: linear elastic (Hooke's law describes the elastic properties of materials since the force and displacement are proportional), Mohr-Coulomb (linear failure envelope, and increments of in-depth compression modules are included), Hardening Soil Model (where the values of the modulus of elasticity of soil are entered from different experiments, as static penetration or oedometer test), Soft Soil Creep Model (uses coefficients to describe the strength of the material: κ, λ, μ) and User-defined model (by setting individual values), while for the construction plate-elements were used. So, the compression modulus values below these columns were taken from oedometer test results, and calibrated considering other tests, such as static cone penetration test, while the material of the aqueduct was considered as linear-elastic. Seismic was included as acceleration, considering previous earthquakes at the location.

After such modelling, the results PLAXIS 2D gave is a horizontal displacement of 34.9 cm on top for the most endangered column C13, which describes the complexity of the problem, considering many different factors that affected the building. As for the second group of columns (inclined towards east), the finding was more precise since the results confirmed the real state of column C26 with a horizontal top displacement value of 22 cm.

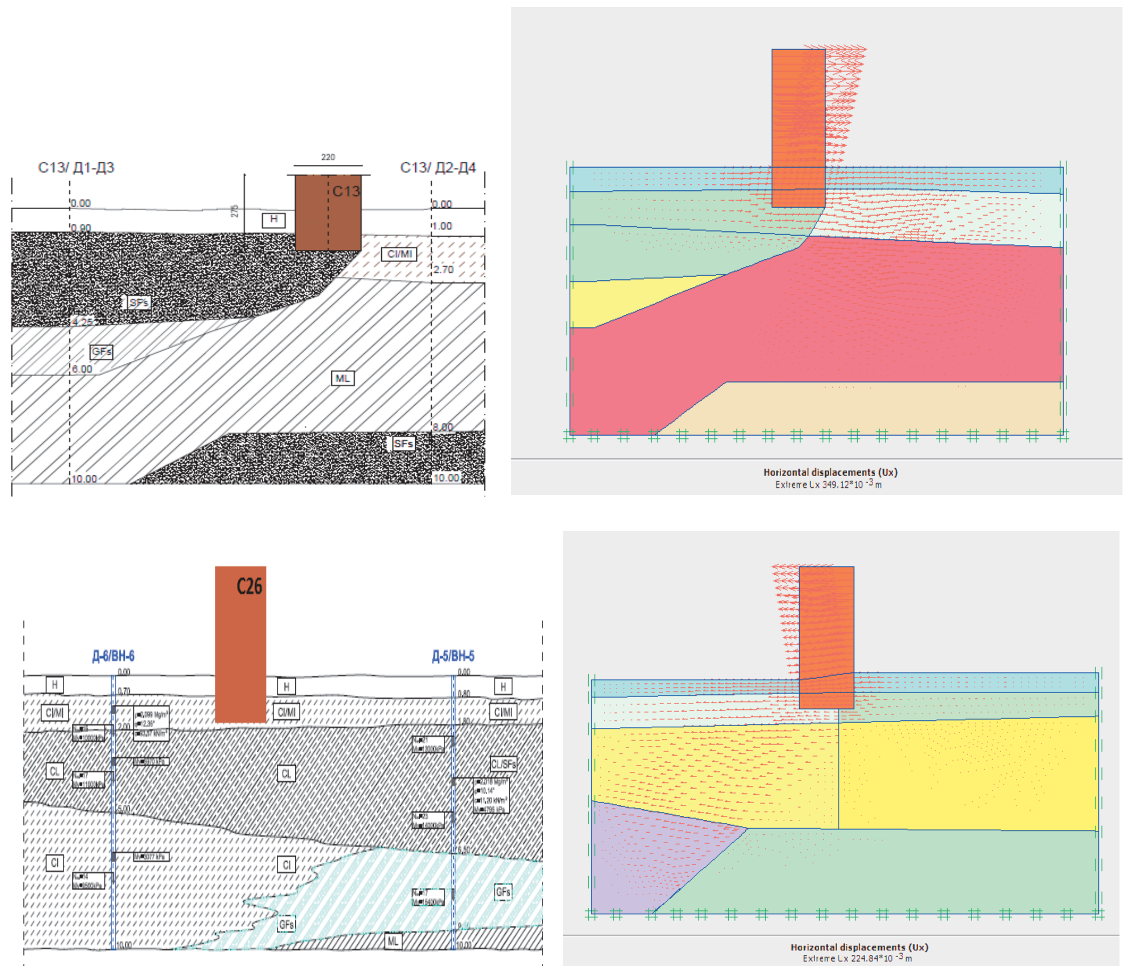

Figure 7 *Complex geotechnical conditions below the columns (C13 – above, left; C26 – below, left) and obtained displacements (C13 – above, right; C26 – below, right)*

To provide a solid solution for this problem, few options were further analyzed in PLAXIS 2D. First, there was an unsuccessful attempt to enlarge the shallow foundation, so two variants of piles were used: large size reinforced concrete piles, and steel self-drilling micro-piles. For each of them two length variants were used: 6 and 8 meters. The results were reducing the 53 cm top horizontal displacement for C13 to only 6 cm and the 22 cm top horizontal displacement for C26 to 4 cm. Given that this is a restoration of a structure that probably dates back to the 15th century, that there are only few data available on the history of deformations and their causes, and that C13 is the pillar with the largest inclination, the results obtained with these piles are considered satisfactory. Confirmation is given also that 6 cm is 1% of the height of the building, i.e. H/100, which classifies them in the category of acceptable ones.

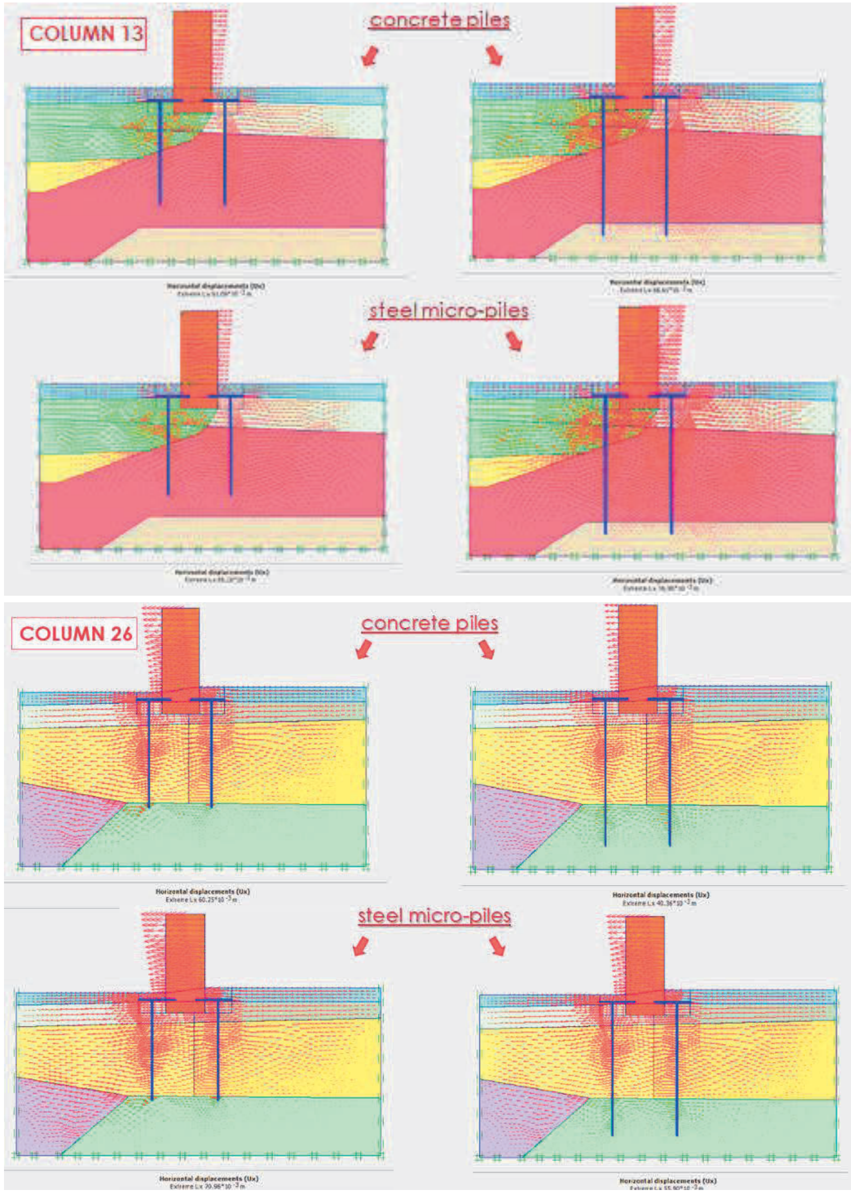

Figure 8 *Calculated displacements after modelling the stabilization measures with concrete piles and steel micro-piles for the aqueduct (C13 – above; C26 – below)*

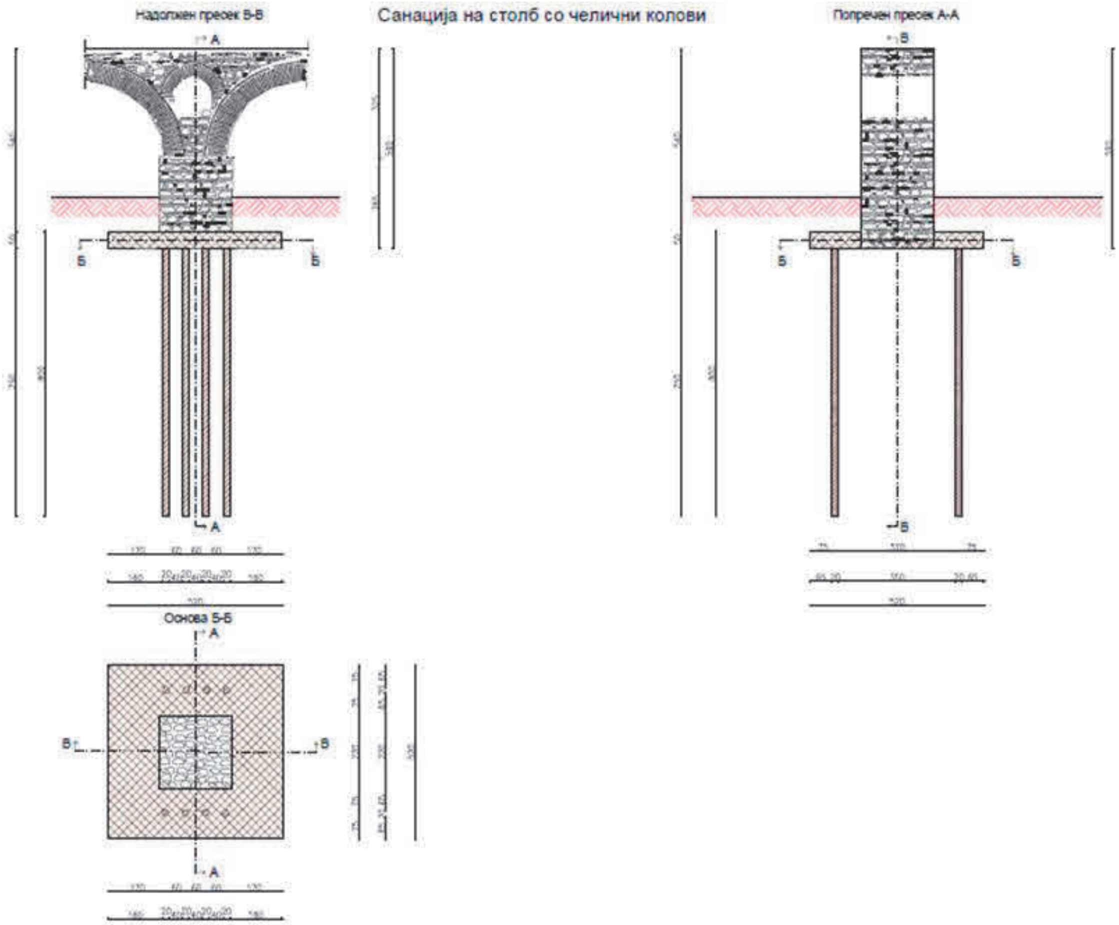

Figure 9 Possible disposition of stabilization with steel self-drilling micro-piles

3. Recommendations

Since the costs between the two applied solutions were comparable, the decision which measure is more acceptable had to be delivered from the execution point of view. From that side, the steel self-drilling micro-piles have various advantages:

- dramatically increased production rates
- lower number of positions which ask application of machines nearby the damaged aqueduct
- the procedure causes minimal noise and low vibration
- drilling and grouting procedures do not cause damage to the existing structures
- easy drilling, regardless of soil type
- there is no excavated material
- special drilling and grouting methods allow the load from the micro-circles to be transferred to the ground (enabled at the soil-pile contact through massive friction)

During their execution, it is necessary to protect the aqueduct with scaffolding etc. However, the list of activities for its full repair is not closed here. Namely, there are also other elements that have to be done for the upper structure, as:

- Restore the damaged or demolished parts of the building. For this purpose it is advisable to use materials with physical-mechanical characteristics similar to the existing ones
- Hydraulic lime with additives can be used as a binder
- Cracks should be injected with an injection mixture based on hydraulic binders

4. Conclusion

The paper presented the numerical modelling of the variant solutions for stabilization of the Skopje Aqueduct. Although the focus is on the stabilization measures, for which steel self-drilling micro-piles were adopted, it has to be stressed that it was rather more difficult to calibrate the model with the registered deformations on the structure due to the very complex geotechnical conditions and limited available data on the history of damages. These analyses served as a base for further design and finalization of the project, which is to be completed and realized during 2021.
Namely, on April 20th 2021, at the proposal of the Office for Protection of Cultural Heritage and the opinion of the National Council for Cultural Heritage, the Government of the Republic of North Macedonia declared The Skopje Aqueduct as a cultural heritage of special importance, subcategory of exceptional importance and the restoration project has started. This grandiose and ostentatious building is considered to be one of the most important archeological sites in North Macedonia, historical and cultural heritage of the country, so it commanded respect: the stabilization measures described above contribute this.

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