A Multidisciplinary Approach to the Restoration of the Pyli Arch Bridge: Integrating Seismic, Geotechnical, and Hydraulic Analyses

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ABSTRACT

This paper presents a comprehensive assessment and restoration strategy for the historic stone arch bridge of Pyli (Agios Vissarion Bridge), a protected monument likely constructed in the early 16th century. Following the extreme flood event caused by Storm "Daniel" in September 2023, the structural safety of the bridge was re-evaluated due to emerging concerns regarding foundation scour and seismic vulnerability.

The investigation integrated architectural documentation, material pathology, and finite element modeling with a detailed evaluation of the geotechnical and hydraulic conditions. A key finding was the asymmetric foundation configuration: the north abutment is seated on competent limestone, whereas the south abutment rests on thick, loose riverbed deposits that are highly susceptible to erosion and dynamic loading. Progressive scour at the south abutment was identified as a primary failure risk, consistent with damage patterns documented in other historic masonry bridges across Greece.

Advanced analyses included staged-construction 3D finite element modeling, 2D soil–structure interaction simulations, and seismic performance evaluation in accordance with EN 1998-1 (Eurocode 8) and KADET for seismic events with return periods of 475 and 914 years. The bridge exhibited satisfactory performance under moderate seismic loading; however, localized instabilities associated with scour-induced foundation degradation were confirmed.

The proposed restoration measures comprise deep ground improvement (jet grouting), protective soil encasement, and perimeter micropiling around the south abutment. These interventions are designed to mitigate flood-induced scour and enhance seismic resilience while preserving the historical and architectural integrity of the structure.

Overall, the proposed multidisciplinary methodology offers a balanced and replicable framework for the preservation of masonry heritage structures exposed to multi-hazard environments.

Keywords: Historic stone bridge, Seismic assessment, Geotechnical conditions, Flood induced foundation scour, Masonry structures, Restoration strategy

INTRODUCTION

The single-span stone arch bridge of Pyli (Figure 1), located over the Portaikos River in the Prefecture of Trikala (Central Greece), represents an outstanding example of mountain bridge engineering from the late Ottoman period (16th–17th century). The bridge features a daring semicircular arch with a height of 22.7 m and a span of 30.8 m. Its slenderness ratio (thickness-to-span) of approximately 1/46 reflects a high level of empirical structural understanding and advanced construction technique for its time (Mantas, 2021). Beyond its structural significance, the bridge served a functional and cultural role, providing access to the nearby Porta-Panagia Monastery and forming an integral part of the historic landscape of Pyli.

Although the bridge has demonstrated remarkable long-term stability, it has sustained localized damage in recent years, particularly following Storm "Daniel" in September 2023. Notable scour phenomena were observed at the southern pier, while the protective retaining wall at the northern abutment was partially destroyed. These damages have raised legitimate concerns regarding the seismic resilience and geotechnical stability of the structure, underscoring the necessity for a systematic assessment and targeted, minimally invasive interventions.

This paper presents a comprehensive investigation of the bridge's current condition and evaluates its load-bearing capacity under static and seismic loading, both in its existing state and after the application of reversible, low-impact strengthening measures consistent with its monumental character. *Specifically*, *this work encompasses:*

- *the structural and material pathology of the bridge,*
- *a synthesis of available technical data — including geotechnical (Egglezos, 2024; KEDE, 2006), structural (GEO.PER. SA, 2024), seismic (Egglezos, 2024; GEO.PER. SA, 2024), and hydraulic (Papakostas, 2024) investigations,*
- *the assessment of the existing structural performance,*
- *the evaluation of proposed intervention measures, and*
- *the main conclusions and recommendations for preservation and risk mitigation.*

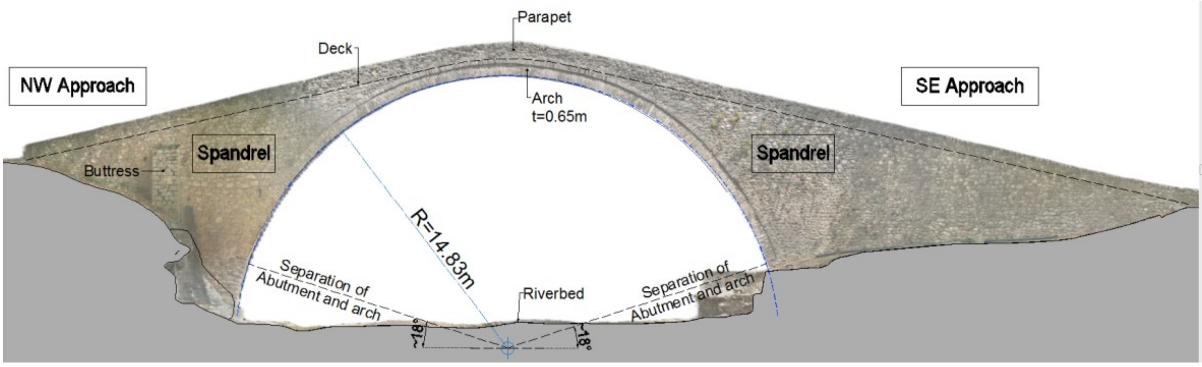

Figure 1. *Upstream view of the stone bridge of Pyli.*

PATHOLOGY

Pyli arch bridge, despite its long-term use and constant exposure to natural factors, currently presents limited structural pathology, mainly in the southern pier, where the most serious problems are identified. From the on-site inspection and the comparative evaluation of data dated back to 2004 (Karaveziroglou, 2004), it is established that the main damages of the previous period have not reappeared. In particular, the significant vertical crack in the inner part of the southern step (Figure 2), which had been observed previously, is not recorded today.

However, scour phenomena have been identified at the base of the southern abutment (Figure 3), posing a critical threat to the bearing capacity and overall stability of the monument. At the northern abutment, an ongoing process of localized detachment of the external stonework is observed, accompanied by vegetation growth, while the foundation rests on *hard rock outcrop* offering better resistance to erosion.

Additionally, at the crown of the arch (near the keystone region), a pronounced transverse deflection of approximately 35 cm is observed toward the upstream direction (Figure 2). This deformation, however, appears to correspond to the original geometric configuration of the bridge rather than a product of recent structural movement.

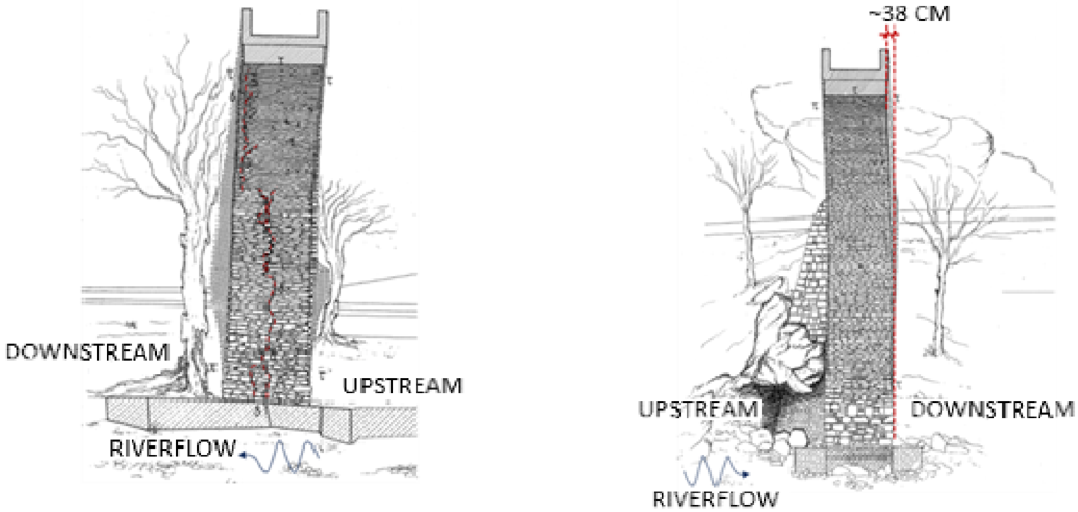

Figure 2. *Transverse deflection – deformation of the arch. View of the Southern Abutment (Left). View of the (Northern Abutment (Right). Figures adapted from Karaveziroglou, 2004.*

A key factor in understanding the structural response of the bridge is the contrast in geotechnical foundation conditions between the two abutments: the northern slope is characterized by competent rocky material, while the southern foundation consists of weaker, erosion-prone deposits. These findings, combined with the evidence of scour activity (Figure 3), confirm the necessity of targeted stabilization and conservation measures to ensure the long-term safety and preservation of the structure

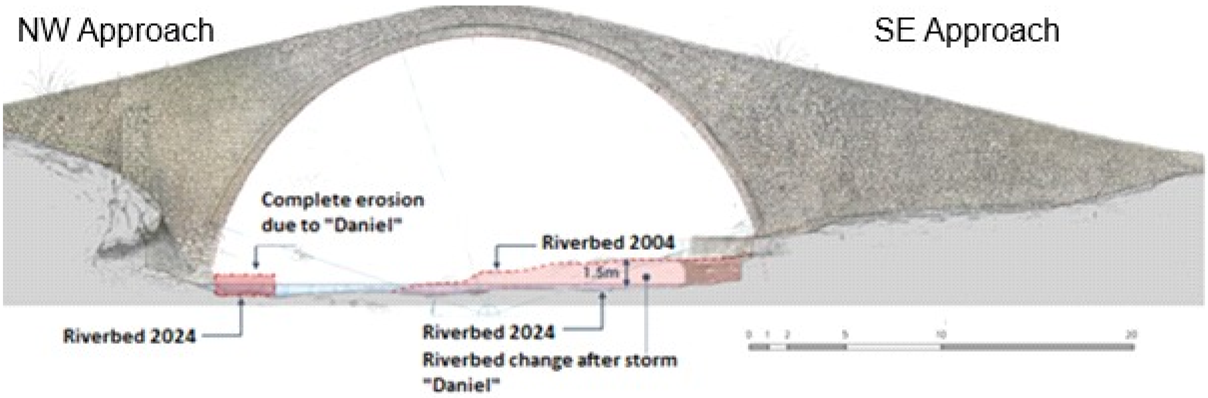

Figure 3. *Overview (upstream view) of the scour zone on the southern abutment, following the storm Daniel (2023). Figure adapted from Structural Study (GEO.PER. S.A., 2024).*

TECHNICAL AND DESIGN DATA

Geotechnical data

The geotechnical conditions at the piers of the Pyli Bridge were investigated through on-site research and laboratory testing, which included borehole drilling, foundation pit inspections, and material sampling (Egglezos, 2024).

At the southern abutment, which rests on alluvial gravel layers—either unconsolidated or weakly cohesive clayey gravels—an exploratory borehole was drilled to document the stratigraphy, foundation depth, and soil characteristics. These deposits are known to be susceptible to undercutting and scour. To further characterize the bearing stratum, data from three additional boreholes located near the bridge within the same geotechnical formation were analyzed (KEDE, 2006).

At the northern abutment, which is surface-founded on rock, in-situ geological surveys were conducted to determine the rock type, discontinuity system (joint sets, orientations, inclinations), and compressive strength, using both impact hammer testing and laboratory analysis of rock samples. The rock mass quality was evaluated using the Geological Strength Index (GSI) classification.

A characteristic longitudinal geotechnical section of the bridge foundation area is shown in Figure 4, while Table 1 presents the derived geotechnical parameters and soil spring constants used in the geotechnical and structural analyses supporting the bridge assessment.

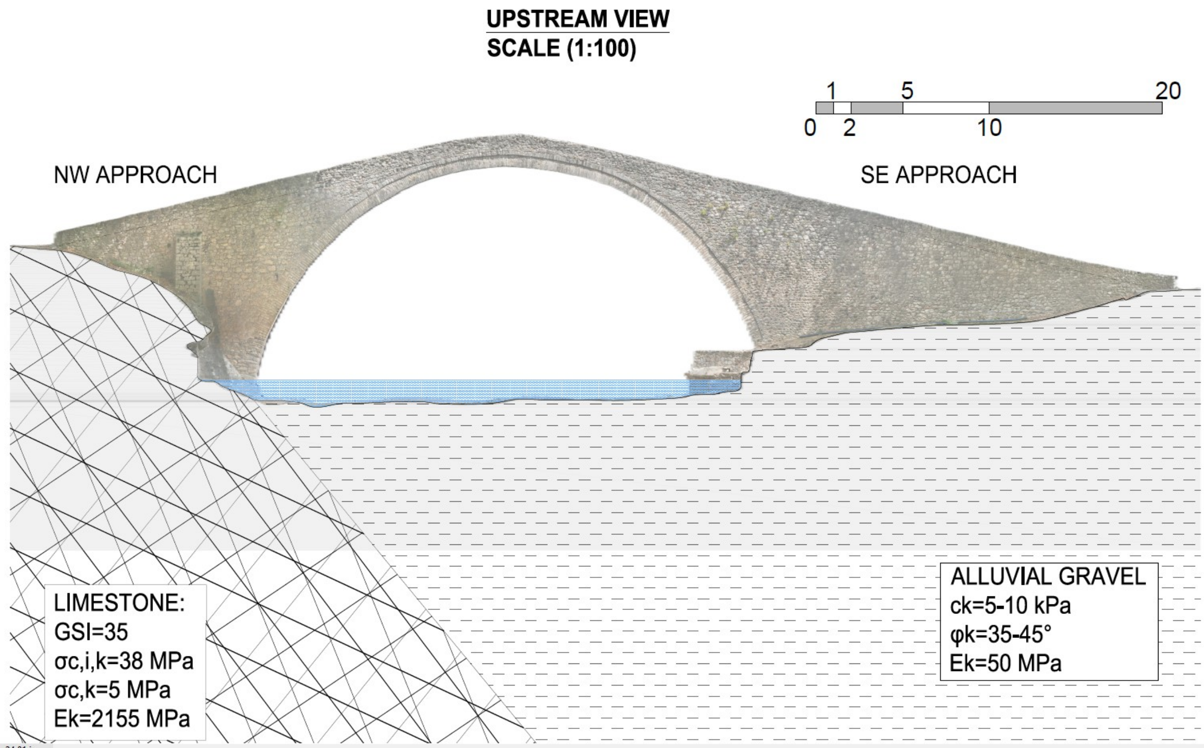

Figure 4. *Characteristic (longitudinal) geotechnical section in the area of Pyli Bridge (downstream view). Figure adapted from the drawings of Structural and Geotechnical Studies (GEO.PER. S.A., 2024; Egglezos, 2024).*

Table 1. *Geotechnical characteristic Properties of foundation soil at Pyli Bridge.*

Soil Layer		**γ kN/m^3**	**GSI**	**E MPa**	**v**	**c_k kPa**	**φ °**	**$σ_{c,1\text{-}k}$ MPa**	**$σ_t$ MPa**	**Kv MN/m^3)**
GL-I	Riverbed Materials (sands and gravels)	22.5	-	50	0.25	5-10	35-45	-	-	30-90
GL-II	Limestone (intact rock)	25	100	20000	0.25	-	-	38	3.2	-
	Limestone rockmass	25	35	2155	0.25	-	-	5	0.03	200-900

Structural data

The Pyli Bridge is a single-span masonry arch structure representative of 16th–17th century construction techniques. The main arch consists of finely carved voussoirs of carefully selected geometry, with piers and spandrel walls constructed of solid stone masonry and internal fill of rubble stone and mortar. The parapets, of low height, follow the slightly curved alignment of the deck.

During architectural documentation, the construction methodology of each component—arch, piers, and parapets—was identified (Figure 5), along with indications of later repair phases. Material sampling provided detailed information on the composition and physical–mechanical properties of the masonry units and mortar. Laboratory tests revealed that the historical lime-based mortar exhibits low tensile and shear strength, which significantly affects the global mechanical behavior of the masonry.

Figure 5. *Characteristic segments of the Pyli Bridge: arch, fill, and spandrel drum.*

The mechanical properties of the masonry were determined through laboratory testing and supported by conservative analytical assumptions to account for hidden discontinuities or internal weaknesses not evident from surface observation (Chousanli, 2024).

Table 2. *Structural Properties of Pyli Bridge.*

Structural Layer	γ kN/m^3	E MPa	v	f_{cm} MPa	f_{tm} MPa	μ	Kv MN/m^3)
Stones	25	20000	0.25	50	3.2	0.3	-
Mortar	25	20000	0.25	50	50	0.3	-
Arch Masonry	23	7000	0.25	7	0.3	0.3	-
Drum Masonry	23	3000	0.25	3	0.3	0.3	-
Filling	23	1000	0.25	1	0.3	0.3	-
Springs North	-	-	-	-	-	-	150
Springs South^A	-	-	-	-	-	-	30^1-90^2
Springs South^B	-	-	-	-	-	-	120

A: Current condition, B:After measure implementation, 1: lower limit, 2: upper limit

Seismological data

The site of the Pyli Bridge lies within Seismic Zone I (a_g = 0.16), according to the Greek Seismic Code (EC-8), corresponding to a moderate seismic hazard. Seismic actions for both assessment and intervention analyses were defined in accordance with Eurocode 8 (EN 1998-1), incorporating the geotechnical foundation conditions and the heritage character of the structure.

Based on the geotechnical data, the northern abutment is classified as Soil Category A, while the southern abutment corresponds to Category C. To ensure a conservative design, the less favorable case (Category C) was adopted for the seismic assessment, corresponding to a design ground acceleration of a_g = 0.184 g.

The historical seismicity of the region (Egglezos, 2024) indicates several significant events of moderate to high intensity, including a major earthquake in 1544 with an estimated magnitude M = 6.4 and an epicentral distance of less than 5 km. The cumulative impact of past seismic activity on the bridge's existing structural condition—particularly damage observed prior to the 2004 restoration works (Karaveziroglou, 2004)—was evaluated and considered in the present capacity assessment.

Two seismic loading scenarios were analysed, corresponding to return periods of TR = 475 years and TR = 914 years. The bridge, in its current condition, was analysed under TR = 475 years, while the proposed strengthened condition was evaluated under both return periods to verify improved performance.

Hydrological data

The Pyli Bridge spans the Portaikos River at a location characterized by a steep transverse bed slope and variable flow depth. Hydraulic loading has historically been a dominant factor influencing the pathology of the monument, particularly affecting the southern abutment (Figure 6).

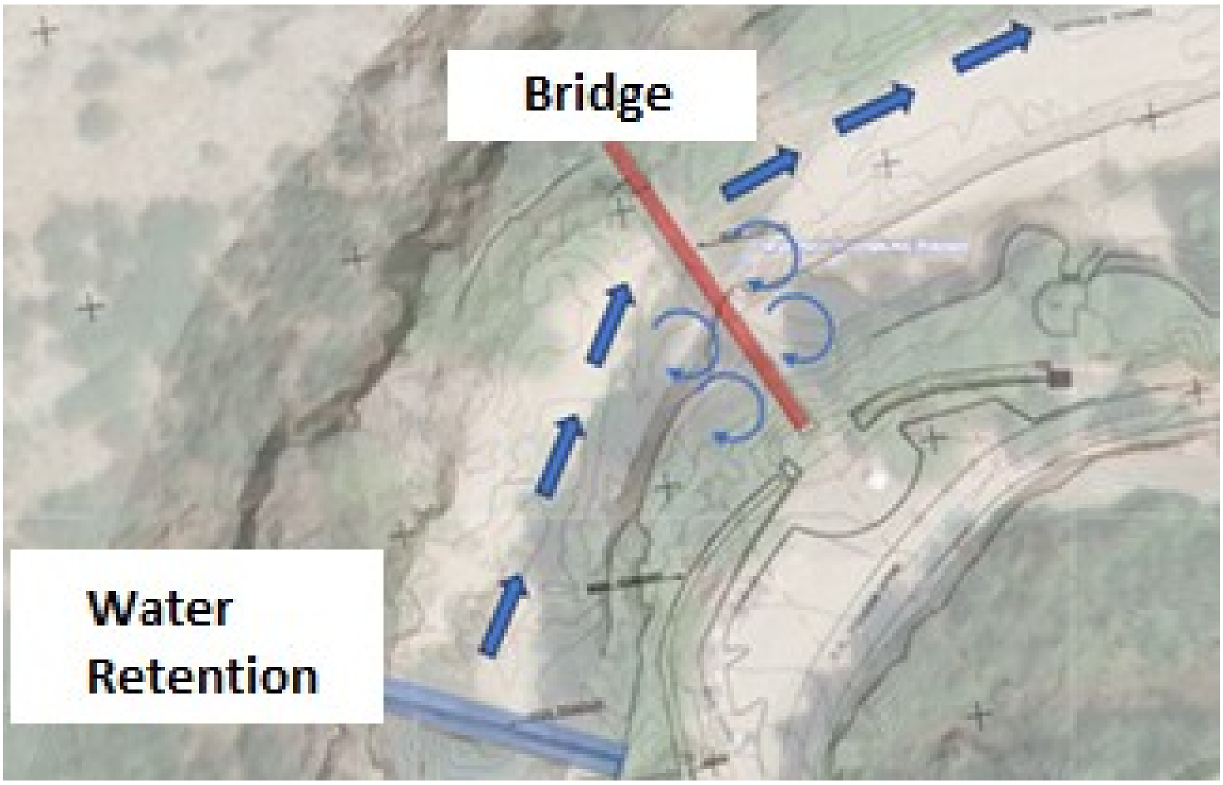

Figure 6. *Characteristics of hydraulic flow near the Pyli Bridge.*

The extreme flood event of Storm "Daniel" (September 2023) caused river overflow and extensive scouring at the base of both abutments, accompanied by erosion of the surrounding slope material. At the southern abutment, substantial loss of soil mass and partial exposure of the foundation were recorded. The northern abutment, though founded on rock, experienced loss of fill material and partial detachment from the natural slope.

These hydraulic phenomena were identified as the primary cause of structural deterioration at the southern abutment. The absence of prior anti-scour protection measures allowed for progressive erosion of the foundation soils over time. The observed hydraulic impacts were integrated into the geotechnical and structural analyses, informing the design of targeted protective interventions aimed at ensuring the long-term stability and resilience of the monument.

NUMERICAL ASSESSMENT OF THE CURRENT CONDITION

The assessment of the load-bearing capacity of the Pyli Bridge in its current condition was performed through an integrated geotechnical–structural analysis, combining data from field investigations with numerical simulations. The behavior of the arch and piers under static, seismic, and hydraulic loads was examined using realistic geotechnical, structural, and seismological parameters.

Simulation of the Bearing Structure

The arch, spandrel walls, and internal fill of the bridge were modeled using finite element analysis (FEA), assuming a homogeneous idealized stone structure with conservative tensile strength values to avoid overestimating the effectiveness of previous interventions (2004). The mechanical properties applied correspond to those listed in Table 2.

The foundation soils beneath the abutments were modeled using elastic soil springs, with stiffness values derived from the geotechnical data of each pier (Table 1).

Regulatory Framework

In the absence of a dedicated structural code for monuments, the assessment followed the principles of the Greek Code for Assessment and Structural Interventions in Masonry Buildings (KADET), issued *by the Earthquake Planning and Protection Organization (EPPO, also known as OASP in Greek). Complementary references included Eurocodes EN 1991–1998, DIN 1045, the Greek Code for Interventions in existing structures (KANEPE), also issued by EPPO/OASP, and the Greek Technical Specifications for public works (ETEP). International conservation guidelines, such as the Venice Charter and the recommendations of ICOMOS/ISCARSAH (2024), were also taken into account.*

Applied Loads

The following loads were considered in the analyses:

- Dead loads: self-weight of the structure
- Live loads: q = 5 kN/m²
- Seismic actions (EN-1998-1, 2):
  - T_R = 475 years → existing state and baseline interventions
  - T_R = 914 years (γ_I = 1.30) → post-intervention only
- Hydraulic actions of 100-year flood with a base pressure p = 240 kPa (increased to account for any dynamic impact). *The hydraulic load was estimated according to AASHTO, 2004, by using the volumetric flow rate that was estimated in the hydraulic study (OLYMPOS P.C.C., 2024),*

Structural Analyses

A linear elastic static analysis was conducted with staged construction phases, simulating two successive phases:

1. Construction of the piers and partial formation of the arch.
2. Completion of the bearing structure.

The seismic assessment included:

- A modal analysis, identifying the critical transverse vibration mode (T = 0.89 s, >75% mass participation).
- An equivalent linear static analysis, performed per KADET with S_d(T = 0.89) = 0.207 and behavior factor q = 1.5.

The T_R = 475-year scenario was used to evaluate the existing condition and baseline interventions, while the T_R = 914-year scenario was applied only for the post-intervention performance check.

Geotechnical Analyses

Bearing capacity checks (EN-1997) identified deficiencies in:

- Southern pier under longitudinal seismic load (TR=475 years)
- Southern pier under the 100-year flood event.

The results (Table 3) confirm the necessity for targeted geotechnical interventions.

Table 3. *Results of Geotechnical evaluation of Bearing Capacity of foundation*

	Normal Loading Conditions	**Flood (T_R=100 years)**	**Earthquake – Longitudinal direction**	**Earthquake – Transverse direction**
		Current Condition		
South Abutment	1.26	0.72	0.52	1.04
North Abutment	9.73	9.28	5.83	6.61
		Implementation of Measures		
South Abutment	9.04	8.04	5.13	8.12
North Abutment	Check is redundant			

Evaluation Criteria and Results

The load-bearing capacity was evaluated using KADET's force and deformation-based criteria. From the three Performance Levels that correspond to the seismic event with return period of T_R=475 years the Performance Level B (significant but repairable damage to the structure) was selected for base check.

For static loads, the maximum compressive stress ($\sigma_{c,max}$ = 2 MPa) and tensile stress ($\sigma_{t,max}$ = 0.19 MPa) (Figure 6) remained below the corresponding strength limits in Table 2.

Using the force method, several characteristic cross-sections of the arch (Figure 7) were analyzed, assuming zero tensile strength. Results showed that most sections remain in compression, with Section 3 being the most critical. The mobilized friction coefficient (μ_{mob} = 0.13, ratio of developed shear to axial force) is well below the maximum available (μ_{max} = 0.30 for cracked masonry).

Localized tensile stress concentrations were observed in the 70°–110° arch sector, with tensile stresses of 0.95–1.95 MPa, where minor cracking is expected and considered acceptable.

The maximum compressive stress (8.07 MPa) occurs in Section 3, slightly exceeding the estimated compressive strength (f_{cw} = 7 MPa).

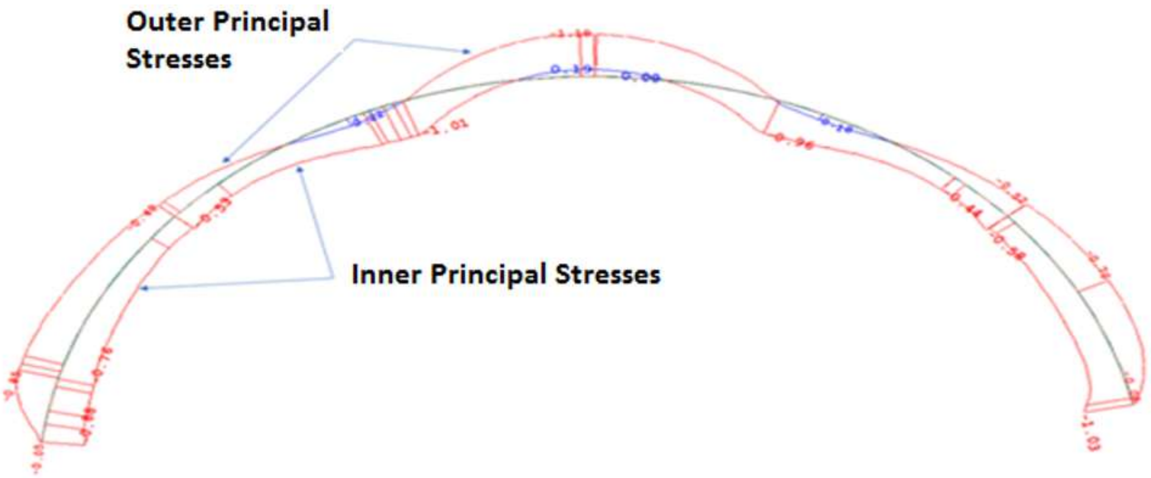

Figure 7. *Principal stresses developed at the intrados and extrados of the arch under gravity loading..*

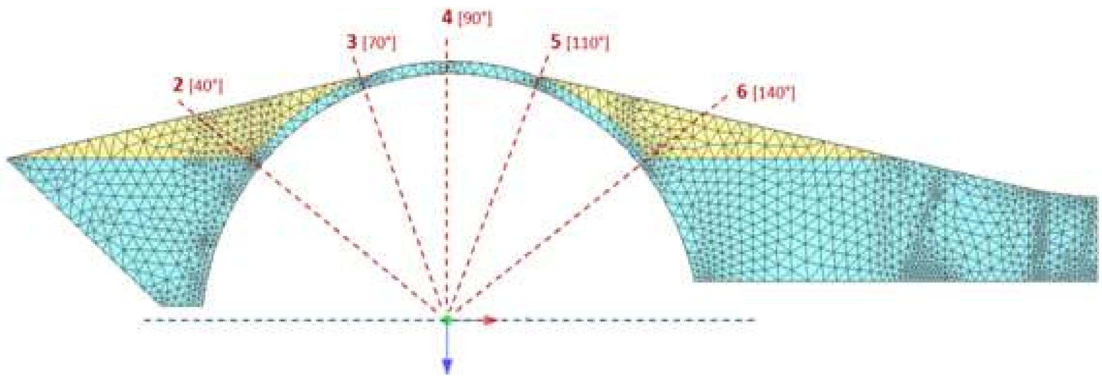

Figure 8. *Characteristic cross-sections of arch under examination*

Based on the displacement method, the maximum transverse displacements at the crown (keystone) remain within permissible limits (Table 4), for both out-of-plane (KADET Figs. S7.9(a), S7.10(a)) and in-plane checks (KADET Figs. S7.5a, S7.7(d)). In order to account for the actual nonlinear behaviour of the structure, the displacements for applying the performance criteria of KADET were increased as shown below by two factors γcr and ρ(T):

$$d_{inel} = d_{el} \cdot \gamma_{cr} \cdot \rho(T) \quad (1)$$

where, γ_{cr} the factor to account for cracking of masonry (is taken equal to 1.4 as of OASP, KADET 2022)
and ρ(T) the correction factor correction to account for inelastic deformations, which is defined in the equations below (1)-(3):

(2) $T \leq 0.5T_C$: $\rho(T) = (\min 2.0\ ,\ 1.5 + 1.0(0.5\, T_C/T - 1))$ (Newmark et al. 1982, FEMA-440 2005).

(3) $0.5T_C \leq T < T_C$: $\rho(T) = 1{,}00 + 0.5(T_C/T - 1)$ (Fajfar et al. 1999, Vidic et al., 1994)

(4) $T_C \leq T$: $\rho(T) = 1.00$ (Veletsos et al. 1960) (Veletsos et al. 1960)

Including the transverse displacements of the spandrel walls, the shear deformation criterion (<0.0040) is also satisfied.

Table 4. *Evaluation of the performance of Pyli Bridge, in its current condition, under the regulatory seismic event with return period TR=475 years*

	In-plane bending (bridge)	**In-Plane Shear (bridge)**	**In-plane bending (cross-section)**	**Out-of-plane Bending (vertical)**	**Out-of-Plane (horizontal)**
Performance level (PL)	B	B	B	B	B
$\boldsymbol{\theta_{limit}}$	0.0685	0.0040	0.0828	0.0257	0.0257
[A]Chord of relative Deformation (θ=Δu/Ho)	0.00019	0.00019	0.00338	0.00369	0.00282
Check Result	✓	✓	✓	✓	✓

[A] Corrected values accounting for the nonlinear behaviour of the structure (according equations 1-4).

Conclusion of Assessment

The Pyli Bridge demonstrates adequate performance under static loading and the regulatory seismic scenario (T_R = 475 years). However, the southern pier exhibits insufficient bearing capacity, primarily due to foundation scour and weakened subsoil conditions.

Therefore, targeted structural and geotechnical interventions are required to ensure long-term stability and enhance seismic resilience of the monument.

PROPOSED INTERVENTIONS – NUMERICAL VERIFICATION

Based on the findings of the structural and geotechnical assessment, and particularly the insufficient foundation capacity at the southern pier, a series of geotechnical improvement measures were designed. These interventions focus exclusively on the foundation zone, avoiding any alteration to the load-bearing masonry structure, thereby preserving the historical integrity and morphological character of the Pyli Bridge.

Description of Interventions

The proposed interventions to strengthen the foundation area (*Figures 9 and 10*) concern: cleaning of the foundation soil; deep jet grouting in the subsoil of the southern pedestal; contact grouting in the northern pedestal; micropiles around the perimeter of the southern pedestal; construction of walls/walls to protect against undermining; and shaping and strengthening the bank with gabions. These measures are reversible, minimally invasive, and designed to mitigate future scour phenomena while maintaining the visual and structural authenticity of the monument.

In addition to the main interventions, following a systematic inspection during the installation of the scaffolding for close access to the structure, the following will be implemented - as general maintenance measures for the structure - where appropriate; Cleaning the masonry from plants, deposits, biological crusts, etc.; Restoration of incompatible joints and/or joints that have been applied in a poor manner as well as worn joints; Replacement of broken stones; Stone stitching of any cracks that are of great length and sealing of cracks.

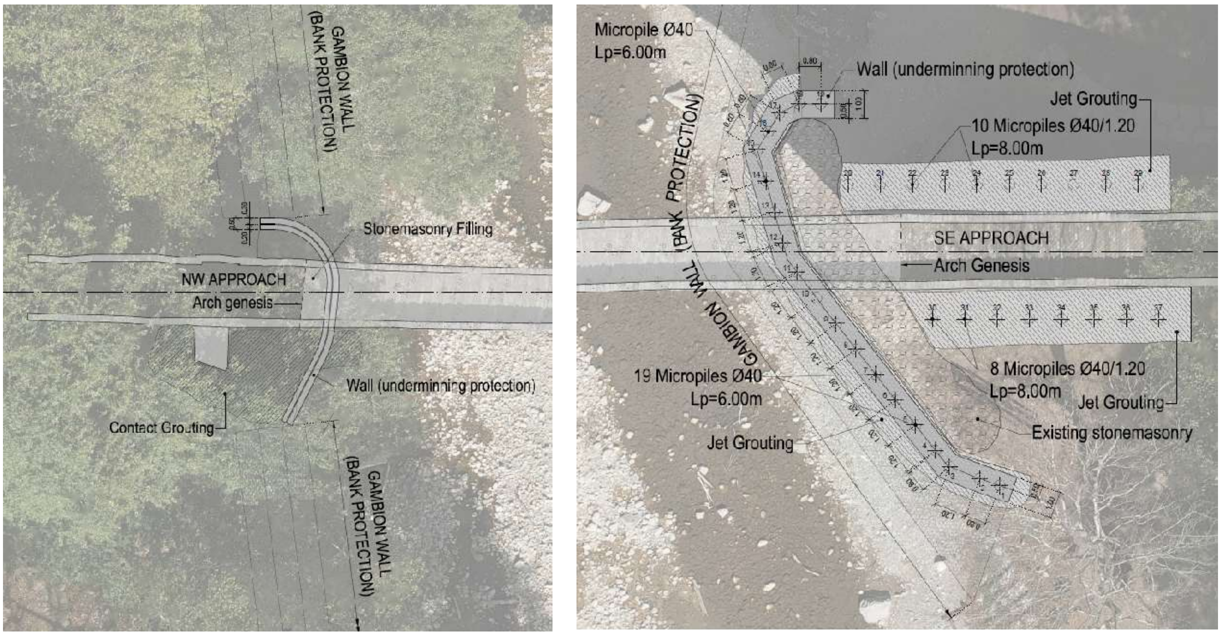

Figure 9. Plan view of the proposed geotechnical measures a) at the northeast abutment and b) at the southwest of the Pyli Bridge.

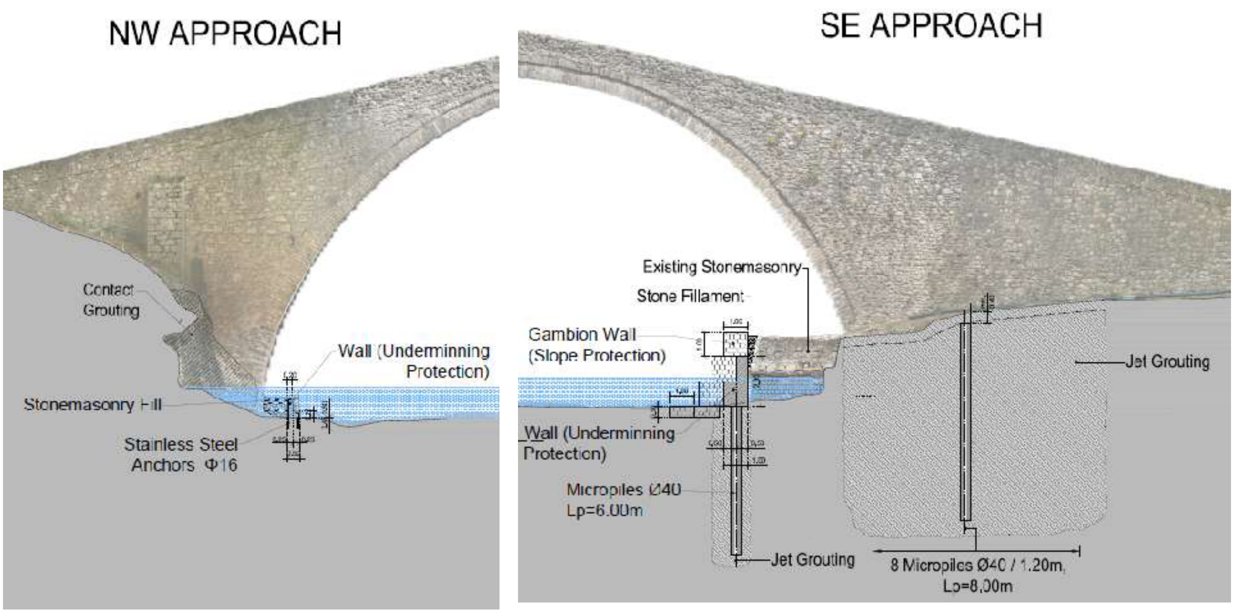

Figure 10. Upstream view of the proposed geotechnical measures. Left: at the northeast abutment. Right: at the southwest of the Pyli Bridge.

Numerical Evaluation

For the numerical verification of the proposed interventions, the finite element model was updated using improved soil stiffness parameters (Table 2), while maintaining the same mechanical properties for the arch and superstructure.

The updated modal analysis yielded a fundamental period T = 0.76 s, and subsequent seismic analyses were performed for return periods of TR = 475 years and TR = 914 years, with corresponding spectral displacements S_d = 0.242 and 0.315, respectively.

Force-based Evaluation (KADET): In all examined cross-sections (Figure 7), the centroid of axial force remained within the masonry section. The most unfavorable sections (3–4) exhibited an inactive surface ratio exceeding 50%, both for TR = 475 years and T_R = 914 years.

The shear checks show adequacy (shear to axial ratio, $V_{tot}/N<0.30$). For the sake of completeness, the critical area of development of high tensile stresses is mentioned (section of the arch between the drums (70° – 110°) with stresses in the range of 0.73 – 1.53 MPa (TR=914) in which -acceptable-cracking is expected. Finally, the maximum compressive stress develops locally in control section 3 (8.24 MPa) exceeding the characteristic compressive strength of the arch (f_{cwk}=7 MPa).

Within the displacement-based evaluation framework of KADET (OASP, 2022), the analyses indicate that, after implementation of the proposed measures, the transverse displacement at the arch crown (keystone) under the seismic action with return period TR = 475 years is reduced by approximately 5% compared to the pre-intervention condition. Furthermore, the target performance levels B1 for the seismic event with TR = 475 years and B1+ for the seismic event with TR = 914 years are satisfied for both in-plane and out-of-plane deformation modes (Table 5). It is noted that both performance levels B1 and B1+ correspond to states of significant but repairable damage, associated with the respective seismic hazard levels.

Geotechnical Evaluation: The implemented measures significantly enhanced the bearing capacity of the foundations, ensuring regulatory compliance under all seismic and hydraulic load combinations (Table 3).

Table 5. *Evaluation of the performance of Pyli Bridge, after implementation of the proposed measures under the regulatory seismic events with return period T_R=475 years and T_R=914 years.*

	In-plane bending (bridge)	**In-Plane Shear (bridge)**	**In-plane bending (cross-section)**	**Out-of-plane Bending (vertical)**	**Out-of-Plane (horizontal)**
Performance level (PL)	B	B	B	B	B
θlimit	0.0685	0.0040	0.0828	0.0257	0.0257
[A]Chord of relative Deformation (θ=Δu/Ho) TR=475 years	0.00012	0.00012	0.00325	0.00363	0.00303
Check Result TR=475 years	✓	✓	✓	✓	✓
[A]Chord of relative Deformation (θ=Δu/Ho) TR=914 years	0.00022	0.00524	0.00494	0.00531	0.00444
Check Result TR=914 years	✓	✓	✓	✓	✓

A:Corrected values accounting for the nonlinear behaviour of the structure (according equations 1-4).

Comparison – Final Assessment

Compared to the initial (pre-intervention) condition, the proposed measures resulted in a notable improvement in seismic response, characterized by:

- Reduced displacements and stress concentrations in critical sections.
- Enhanced foundation stability and resistance to hydraulic erosion.
- Compliance with performance criteria for both static and seismic actions.

The masonry arch remains morphologically and functionally unaffected, and the overall intervention strategy ensures long-term structural safety, heritage compatibility, and environmental resilience.

CONCLUSIONS

The structural assessment of the Pyli Bridge demonstrated that the arch and superstructure exhibit satisfactory performance under both static and seismic loading. The primary deficiency lies in the foundation of the southern pier, where unfavorable geotechnical conditions and progressive scour, intensified by the Storm “Daniel” (2023) event, have compromised stability. The earlier restoration effort (2005) proved inadequate, as it did not address the underlying foundation vulnerability.

The proposed intervention strategy focuses on geotechnical enhancement—including deep grouting, micropile reinforcement, gabion installation, and slope stabilization—without any modification to the masonry arch. Numerical analyses and verification confirmed a substantial improvement in bearing capacity, accompanied by reduced displacements and enhanced seismic resilience.

The adopted methodology, based on the principles of minimum intervention, compatibility, and reversibility, establishes a sustainable restoration model for historic masonry bridges, ensuring structural safety, seismic protection, and the preservation of architectural authenticity.

Furthermore, complementary conservation measures—including joint repointing, crack sealing, deck waterproofing, and the systematic removal of vegetation—are recommended to ensure the long-term durability and protection of the monument.

ACKNOWLEDGEMENTS

We would like to thank the Ephorate of Antiquities of Trikala, and in particular Ms M. Papastergiou, for her professionalism, scientific contribution, and continuous support during the preparation of the underlying study. We also acknowledge Mr Manolis Tzannidakis, Civil Engineer (MSc), for his assistance with the preparation of the illustrative material and the formatting of the manuscript, as well as for his contribution to the study that formed the basis of the present communication.

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