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Medijana-Niš Archaeological Site Protection Membrane Structure

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Summary. The "Medijana" project was designed to protect one of the most important archaeological excavation sites from the ancient Roman period in Serbia, and presented a significant challenge due to its location as a candidate for UNESCO heritage protection. In 2023, the project has been completed, with total covered surface of 12,000 m2, a main clear span of 80m and a length of 148m, one of the largest membrane structures in this region of Europe. The site-specific limitations and conditions required careful planning and logistics. As such, this project serves as a unique case study that illustrates the interplay between design, limitations, and consequently the need for innovative detailing and installation techniques. Through monitoring and observation over a period of 9 years, a wealth of information including wooden structure – membrane interaction, microclimatic conditions, and maintenance has been collected, which will be valuable for future developments, the field of membrane structures in cultural heritage applications and beyond.

1 INTRODUCTION

The archaeological site "Medijana" is located in the city of Niš in Serbia and is one of the most important sites from the ancient Roman period [1]. It is the birthplace of Constantine the Great, one of the most important Roman emperors who liberated Christianity and founded Constantinople, today's Istanbul, as the new capital and one of the most impressive cities of the present day. It is still a mystery whether the ruins and mosaics of the "Villa with Peristil" in Medijana, actually is the birthplace of the great emperor. The excavation operations at this site commenced nearly a century ago. Over the course of all these years, efforts were made to fully comprehend the significance of this location and establish the necessary measures to enhance its level of protection. Today the site is a candidate for UNESCO heritage protection [2].

The "Medijana" project introduces approaches to safeguarding this significant archaeological site through the implementation of a membrane cover. While the utilization of membrane structures for protection in archaeology is not unprecedented, this particular project presents an entirely new experience and insights in this field due to the sites´ size, specific location, installation conditions, special requirements, and various restrictions.

The primary goal of the project was to establish a comprehensive protective structure encompassing the entire site. This structure aimed to provide improved conditions for excavation, conservation, and effective presentation for both scientific and touristic purposes. Given the project's intricate nature and scale, it consumed nearly a decade of work conducted in three phases. Overcoming administrative obstacles, budget limitations, and challenging multidisciplinary approach, the engineering challenges proved to be exceptionally complex and demanding.

Figure 1: Base of atrium column (left) and segment of mosaic (center), interior, conserved floor mosaic below membrane cover (right)

This paper explains this complex process from design to production to installation and maintenance. What makes this project special is that although the client's requirements were defined at the beginning of the project, new situations regarding excavations, disciplinary requirements and administration resulted in continuous changes and additions during the design and construction process. Despite our experience with this type of structures [3], new and often unexpected situations arose, so special efforts were made to dynamically adapt all activities and the structure itself to the ongoing process. The project exhibited a dynamic and dynamic nature, characterized by active transformations. The evolving nature of the excavation activities required continuous adjustments and innovative solutions to respond to new challenges. Ultimately, this process can be described as a continuous cycle of adaptation, learning, and development. The project not only provided valuable insights, but also led to a novel paradigm of experience at an unprecedented level.

2 DESIGN PROCESS

2.1 Project tasks

Initially, the primary objective of the project was straightforward: to shield the excavation site from environmental elements like rain and snow. This basic requirement met the needs of the archaeologists and the workers involved in the excavations. However, when the importance of the "Medijana" site as a remarkable archaeological jewel became clear, various local and national institutions joined forces. Finally, several key entities participated in the project, each with its own distinct roles and responsibilities. The City of Niš [4] played a crucial role as the initial point of contact and support for the project. Subsequently, the Regional Institute for Monument Protection [5], Republic Archaeological Institute, National Museum of Niš [6], and finally, the Ministry of Culture of the Republic of Serbia [7] all contributed their expertise and resources. However, the collaboration and communication between and with these involved parties was intricate, as each institution follows specific jurisdictions and catered to unique requirements related to the project. And despite the complex relationships, the specific needs and desires of each institution needed to be considered. The project encompassed several defined aspects, each with its specific requirements and considerations. These aspects included the Archaeological aspect, the Architectural aspect, the Monument Protection aspect, the Presentation aspect, and the Maintenance aspect. Throughout the project, new phases triggered additional requests and adaptations to the project's objectives.

- In the Archaeological aspect, the focus was on defining the necessary conditions for excavation work. The project aimed to provide a shelter that would facilitate year-round excavation activities without impacting future excavation areas.
- The Architectural aspect emphasized the need for the new protective structure to not only serve its primary function but also blend aesthetically with the city environment, paying homage to the architectural heritage of antiquity.
- The Monument Protection part emphasized the importance of preserving excavated artifacts on-site. The structure needed to maintain the authentic positioning of the materials while safeguarding them from potential detrimental influences.
- The Presentation part outlined expectations and conditions for the future utilization of the facility. It aimed to create a museum-like building capable of accommodating tourists, scientists, and other interested groups. The presentation of artifacts in a detailed and contextual manner within the villa was a key objective.
- The Maintenance aspect highlighted the responsibility of the City Museum of Niš to operate and maintain the facility. Requests in this regard focused on minimizing maintenance expenses and utilizing technologies and materials that ensured the structure's longevity.
- Additionally, the project incorporated special attention to future development. As the excavation field will expand in future, the structure needs to be flexible enough to follow possible expansions.

Spanning several phases over a nine-year period, the project's design demonstrated high adaptability to accommodate ongoing developments and fulfill the evolving requirements of the various project areas.

2.2 Challenges

The importance of this project led to the involvement of numerous participants with different priorities and interests. Coordinating and meeting all requirements proved to be a challenging but invaluable experience. Examining the challenges encountered may provide insight into the complexity of the project.

The first observation may draw the attention to the size of the structure. With an impressive span of about 80 meters and a length of 130 meters, it represented a substantial undertaking, as at the start of the project, it was the largest structure of its kind in this region of Europe. The considerable size of the structure presented logistical challenges in terms of transportation, production and handling, and required a careful solution to these problems.

Designing a structure while considering constantly changing requirements is rooted in the multidisciplinary nature of the project and the involvement of numerous experts and disciplines involved in parallel activities required a flexible approach to the design process.

The installation process outlined in the design phase also proved to be extremely challenging. Since the excavated mosaics and ruins were scattered throughout the area to be covered, any construction activity in these areas was prohibited. Consequently, common installation concepts had to be completely revised and alternatives created.

A similarly complex challenge arose in locating, designing and constructing the foundations for such a large structure on an unexplored archaeological site. Comprehensive protection and careful exploration of the unexplored layers were indispensable prerequisites for such measures.

Preservation and protection of conditions, such as avoiding condensation, UV radiation, and abrupt temperature changes, were achieved without the use of air conditioning and HVAC equipment. Instead, the natural, mechanical, and physical properties of the structure and its surroundings were utilized. Ensuring optimal microclimatic conditions within the building was critical for all future activities below the cover.

Managing atmospheric water runoff was another problem that had to be solved. The extensive sealed roof area results in significant amounts of stormwater. This must be drained without endangering the existing or future excavation areas and, at the same time, without using conventional drainage systems.

Harsh weather conditions presented a significant challenge, especially when constructing a structure as large as the presented one. In addition, due to its proximity to a municipal water source, the "Medijana" site was subject to strict control and monitoring measures that went beyond archaeological considerations and usually required special permits from the municipality.

2.3. Design loops

The design process for the protective structure for "Medijana" presented a truly unique experience. It involved multiple iterations, numerous adaptations, changes, and the absence of established standards for such structures. It merged functional, material and structural knowledge into various design proposals [8–11]. Additionally, new legal regulations and the participation of various stakeholders further characterized this complex undertaking.

The initial design concept featured a spatial structure as shown below, consisting of several interconnected parts intended to cover the entire excavation site as it was known at that time. The choice of Glue laminated timber (GLW) as an authentic material reflecting the characteristics of the ancient era, combined with the utilization of membranes, aimed to create a multifunctional and lightweight solution. This approach provided protection against rain, hail, snow, and intense sunlight. The project served as the foundation for subsequent processes, including obtaining numerous approvals, licenses, and fulfilling various administrative procedures.

Besides other changes and concepts, a significant modification occurred with the reduction of the covered area. Due to budget constraints, it was decided that the smaller side portions would not be included in the initial phase of the project. Consequently, the structural system had to be redesigned to exclude these side parts. This decision necessitated a complete overhaul of the structure's design, resulting in a new and distinct architectural solution.

As the project progressed through its intricate procedures, it reached the stage of selecting a contractor company through a competition. However, an additional obstacle emerged when the Institute for Archaeology stipulated a crucial condition for the construction process: all works and approaches to the building site must be situated outside of the excavation area. Given the dimensions of the covered excavation area (80 x 148 meters), this requirement shed new light on the feasibility of the initially presented design. The original design featured a complex wooden spatial structure comprising numerous joints and interconnected elements, forming a sophisticated geometry for the lightweight large-span shelter. However, with the new request to keep all construction activities outside the excavation area, the installation of the initial design became impossible. Consequently, another iteration of the structure's design was undertaken. While the shape, size, and materialization remained largely unchanged, the structural system was entirely reimagined. The primary focus shifted towards ensuring the feasibility of the installation process. A new solution was defined and presented for the execution design, incorporating the necessary modifications to meet the revised requirements.

The planning process significantly extended, considering the considerable size of the structure and the expected atypical installation timeline. Anticipating the potential occurrence of influential factors such as strong winds or snowfall during the installation, it became necessary to delineate distinct phases and assess the structural stability under various critical scenarios. Only after completing these evaluations could the assembly procedure start.

While the construction of the large span constituted the primary challenge, other aspects of the project also presented significant complexities. The foundations had to bear the substantial loads of the large-span structure while avoiding any interference with essential excavation layers. Given the expectation of notable horizontal forces in the foundation, the placement of foundation footings within the ground became critical. Utilizing data obtained from georadar surveys, the optimal positioning of these footings was determined. The process of mapping the underground structure entailed identifying suitable foundation locations. More details on this topic will be explained in the following chapters.

Considerable time and meticulous attention were dedicated to the environmental conditions, with particular emphasis on lighting. Ample daylight was necessary to ensure visibility beneath the structure for excavation and preservation activities, as well as for future presentations to visitors. In line with this requirement, a specific architectural membrane type, namely Type 3 supplied by Sattler AG, was selected. This choice allowed to simultaneously meet multiple conditions. The tensile strength of the chosen membrane proved suitable, while its translucency provided sufficient natural light and effective shading, particularly during intensely illuminated summer days. Moreover, the membrane offered crucial UV protection, preserving the color pigments on the excavated mosaics from potential damage.

Another critical aspect related to the ambient conditions was ventilation and temperature control. Similar to the approach taken with natural light, the principles of natural ventilation were applied in the design. The arrangement and dimensions of openings were carefully planned to facilitate the natural circulation of air at specific levels and directions. This was essential to mitigate or minimize issues such as overheating and condensation.

As above-mentioned, the water drainage posed a unique challenge in its implementation. Given the substantial amount of water from rain and/or snow on the roof surface careful measures were taken to ensure that the water did not impact the floor level with the mosaics. A solution was devised by constructing a soil barrier at the lower openings and forming a trench on the outer side beneath the floor level. This allowed the water to be directed away from the structure and drained into the surrounding grass fields. Additionally, adjustments were made to the geometry of the side openings to reduce the impact of snow, rain, and direct sunlight. These modifications necessitated a new design for the membrane segment pretensioning system. The efficacy of the implemented solutions and their performance in relation to environmental parameters will be elaborated upon in the subsequent sections.

3 PRODUCTION

The technological approach selected for this project was a prefabricated lightweight structure, offering several advantages. One of the main benefits is that a significant portion of the construction process occurs within controlled conditions at production facilities. Consequently, this minimizes the likelihood of encountering unexpected or unforeseen situations during this particular stage. The production process itself was performed in three parallel processes: foundation forming, GLW construction, and membrane surface production.

3.1 Foundations

The foundations proved to be the most unforeseen aspect of the project. Given the significant horizontal forces identified in our structural analysis, a portion of the foundations needed to be positioned partially underground. The design concept aimed to minimize the surface area of the foundations by placing "base foots" directly beneath the supporting points of the arches. Georadar scans were conducted to ensure that each foundation was positioned in an area free from potential archaeological artifacts. Nevertheless, the excavation process was executed with utmost care under the continuous supervision of both engineers and archaeologists. As shown below, the size of the footings was considerable, measuring approximately 3.5 x 5 meters, as there was no underground connection such as a connecting tie between the individual supports possible, for further reducing the need for extensive excavation in the local soil. It is important to note that the entire terrain is located in a protected water source area, situated in close proximity to a river. Adding to the complexity, the underground water level began to rise, affecting all excavation holes. Consequently, water had to be pumped out intensively to ensure proper casting of reinforcement and concrete.

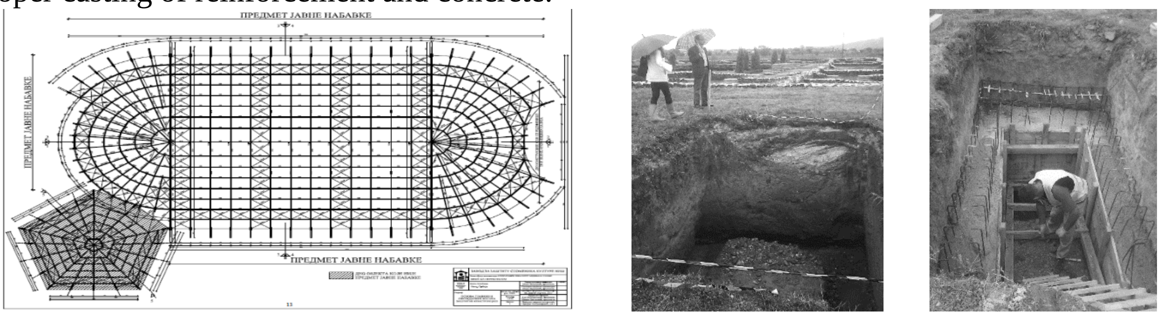

Figure 2: Initial design, disposition of GLW construction, excavation for foundations and casting phase

3.2 GLW structure

The production of GLW arches and secondary construction elements followed a standard procedure, with no unexpected surprises except for the unusually large size of all the elements involved. The construction consisted of 14 arches, each composed of three segments. Each segment measured approximately 29 meters in length, with the largest cross-section profile measuring 20 x 240 centimeters. These arches spanned up to about 80 meters. The biggest challenge in production was handling these large elements within the production facilities. In addition, the dynamic nature of the production process required careful analysis and coordination. The structure had to be produced according to a precise schedule for several reasons. First, timely delivery to the site was critical to ensure that the installation process could proceed as planned. Due to space constraints and the need for suitable conditions, it was not possible to store the GLW elements on site for an extended period of time. They had to be installed immediately after delivery. In addition, storing such a large quantity of GLW elements in the production facility would make handling difficult and possibly disrupt production. Therefore, the entire production flow had to be carefully managed to ensure a smooth and coordinated process. A particular challenge was the production of connecting plates, joints and other related detailing. Given the immense size of the structure and GLW elements, non-standard plate and profile sizes were required for all joints and fittings. Therefore, special efforts were made to manufacture these elements, mainly in steel, as well as other necessary components.

3.3 Membrane elements

As with the GLW structure, the manufacture and processing of the membrane elements was more or less standard. The entire membrane was divided into 13 equal panels, with additional characteristic segments on the radial parts, i.e. another 19 panels. A greater challenge was the definition and production of the pre-stressing elements and the associated assembly. As with the GLW production, many parts were oversized and non-standard.

4 INSTALLATION PROCESS

4.1 Preparatory tasks and works

The installation process posed significant challenges due to restrictions on accessing the covered space. Preparatory work included creating an access road to accommodate the delivery and manipulation of construction materials and machinery. As the site was agricultural terrain unsuitable for heavy traffic, a temporary gravel road was constructed to prevent vehicles from getting stuck. The next step involved preparing the area for assembling the main GLW arches, and to slide them on temporary tracks and rails to their final position on the foundations. Given the size of the structure, thorough testing was conducted on-site prior to final installation, covering aspects such as motion stability, consolidation position stability, tensioning elements, water drainage systems, support structures, protection structures, and unloading platforms.

4.2 Installation of the GLW structure

The construction installation plan involved first installing the middle part consisting of 14 arches, closed by a radial calotte on each end. Due to restrictions on the use of machinery and scaffolds inside the area, a strategy was devised to construct the arches outside the mosaic area and then slide them into their final position. The main arch was composed of three segments, each approximately 29 meters long, with a section profile of 20 x 240 cm. These large elements were positioned near the joining platform to facilitate the installation process.

Figure 3: Special transportation of GLW elements on truck (top), preparation of first set of GLW arches (left, center left) and wagons under arch supports for moving and positioning of auto stabile set (center right, right).

Figure 4: Scheme of alternating membrane panels installation (left, center), auxiliary membrane structure with marine ladders (right)

The next step in the installation process involved forming the main arch in a vertical position. The outer segments were positioned first, followed by the middle part. An auto crane provided support for the middle part until connection plates were installed. The same procedure was repeated for joining the second parallel arch. Simultaneously, the arches were connected with linear secondary elements and stabilized with tensioning bands, forming a self-stabilized set.

Additional diagonals and steel profiles, such as bowstrings, were added to enhance stability and prevent deformation. Once this segment was ready, it was slid along the temporary concrete tracks. Four specially designed wagons were installed under the ends of the connected arches to facilitate movement. Hydraulic traction presses were coordinated to ensure controlled and synchronized movement on both sides of the segment.

Positioning the arches on the supports followed a complex procedure. The transported segment was initially slightly higher than the final supports. Hydraulic jacks were used to lower the segment to the supports, requiring precision and accuracy within centimeters. Once fixed, this set of two arches provided stability for the subsequent installation steps. The same procedure was repeated for the remaining arches, gradually expanding the structure and increasing its stability. Accessible from outside the mosaic area facilitated the installation of arch elements for the end-calottes.

4.3 Installation of membrane elements

The installation plan for the membrane segments had to be carefully coordinated with the installation of the GLW structure, considering the different behavior and sensitivity of the installed segments at each stage until the completion of the entire structure. Following the sequence of the timber structure, the installation of the membrane was launched. Safety and the prevention of damage or progressive collapse were of utmost importance at each stage of the installation. To ensure this, a partial covering was chosen. Installation began with the first bay, then skipped to the next bay and continued with the third bay. This alternating cover pattern added stability to the installed bays and reduced snow load, wind load and possible turbulence, especially at the uncovered bays.

Upon the completion of the GLW construction, allowing it to reach its designed stiffness, the installation of the remaining membrane segments followed. Each segment was fixed onto the GLW arch using a specifically designed aluminum profile with a keder, and tensioned on two opposite shorter sides. It is worth noting that opting for a longer tensioning direction was an unconventional decision. Typically, it would be more logical to have pretensioning in four directions, primarily on the shorter span. However, for the purpose of expedited installation, ease of maintenance, and improved connection details with the GLW arch, the choice was made to utilize a special cast aluminum profile for the connection. The challenge was to achieve sufficient pretensioning in the longer direction, which was overcome through the implementation of special panel geometry and patterning. Additionally, the design of tensioning rods and related components played a crucial role in ensuring the desired tension forces were achieved.

Not using scaffolds and machinery posed a challenge during the membrane installation phase, although to a lesser extent compared to the GLW installation. To overcome this limitation, wooden supports were utilized in critical areas to establish auxiliary systems for the membrane installation. The use of nets as an auxiliary tool was discouraged due to the risk of hand tools or small fitting parts falling through and potentially damaging the mosaics. Instead, an unconventional solution was implemented by preparing a membrane scaffold using maritime ladders, which proved to be an efficient aid in the installation process.

5 MONITORING AND OBSERVATIONS

The environmental conditions surrounding the structure presented various challenges related to soil, humidity, dirt, exposure to sunlight, wind, rain, snow, and fog. The abundance of water sources in the vicinity, including water springs and a nearby river, along with the flat terrain, contributed to high local humidity. This unfavorable condition led to temporary condensation within the facility. Although it was not possible to completely prevent condensation due to the open design of the structure at ground level, several measures were implemented to mitigate its effects. Ventilation openings were strategically incorporated into the membrane at high points, allowing for the elimination of significant vapor that directly contributed to condensation. Additionally, natural air ventilation at ground level helped dissipate vapor and minimize the likelihood of condensation on the mosaics. The dew point in the local area was typically around 14-16°C, but with the formation of the dome structure, the dew point was reduced to approximately 13°C. This slight decrease in temperature significantly reduced the occurrence of condensation. Although complete elimination of condensation would require the closure of the hall and mechanical air conditioning, the implemented measures have successfully reduced condensation levels and are crucial for preserving the existing mosaics in the long term.

The Medijana structure is located within agricultural land in all directions. This location, which was advantageous in terms of protecting and preserving the valuable mosaics from wind exposure, today poses the challenge of accumulation of dirt on the membrane roof. This reduces the amount of daylight below the structure. However, after nine years of monitoring the condition of the membrane, it has been determined that there are no visible chemical or physical reactions. Therefore, regular maintenance and cleaning of the membrane can restore its initial light transmission capabilities. Color changes are in the expected range for membrane structures.

During the past nine-years, the behavior of GLW in the half-open structure was closely monitored. The project initially anticipated different conditions for the GLW, including covered elements, uncovered vertical elements, and fully uncovered elements. The covered wooden elements were found to be in stable and safe conditions. The main concern was their reaction to high humidity. However, with the reduction in humidity levels as previously explained, there were no significant concerns regarding the impact of humidity on the wood, also due to a special foil was inserted at the interface between the PVC membrane and the wood to control humidity levels and prevent condensation at this point. Our concerns were greater for the parts of the construction that were planned to remain uncovered for several years. As expected, after exposure to rain, snow, and sunlight, some local damage to these elements was observed. However, the vertical elements experienced no relevant structural damage so far.

The temperature behavior in the open structure without air conditioning was observed and measured. While there were no strict expectations for temperature control, tests were conducted to assess the temperature stability within the structure [12]. The results of the measurements revealed a certain degree of temperature stability within the inner air of the structure. The temperature of the inner space showed less oscillation compared to the daily temperature changes observed outside. The below diagram depicting the temperature data over a three-day period in summer shows the outside temperature represented by the green line, while the red line represents the temperature inside the structure. An interesting observation from the data is that during the period of the lowest outside temperature (13°C), the temperature inside the structure remained at 16°C. This indicates that the inner temperature was above the dew point, preventing condensation from occurring within the space, as explained earlier. [12]

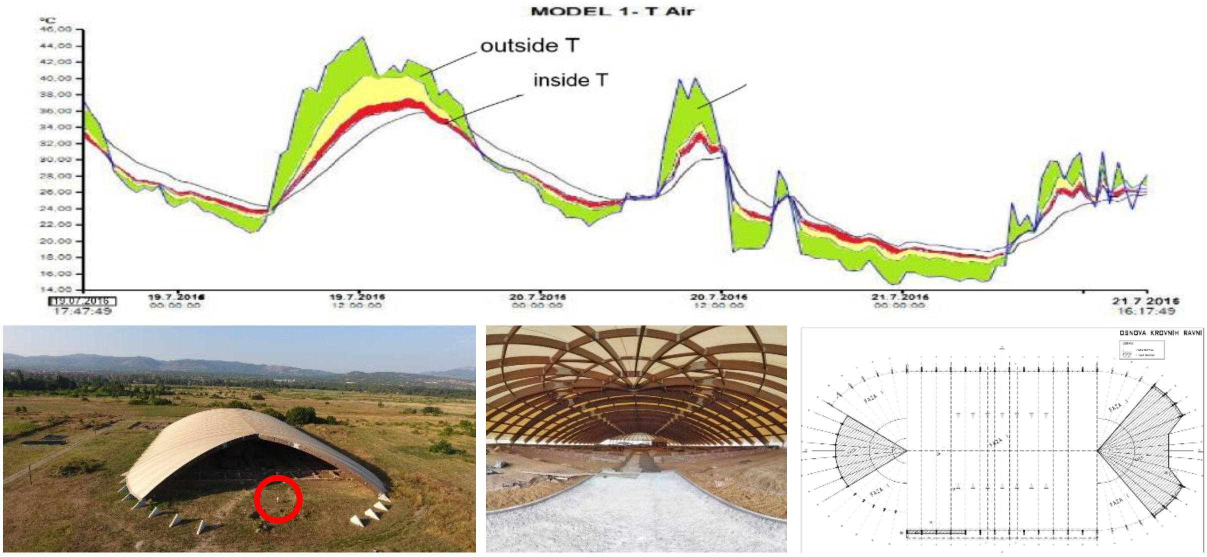

Figure 5: Temperature behavior example of three days period (top), structure at the end of phase 1 with visitors (in red circle) (left), entrance area (center) and roof plan with phase definition (right).

6 CONCLUSIONS

The installation of this large structure posed challenges due to restrictions, limited access space, and the absence of heavy machinery. These circumstances led to the adoption of ancient low-tech approaches [13] suitable to the "Medijana" archaeological site to successfully install the structure. The project was completed within six months, and the membrane installation team consisted of 5-7 individuals, while the GLW installation team comprised 10-12 individuals. However, mentioned techniques are in clear contrast to the following specifications of the structure, which provide an overview of the scale and complexity of the installation process.

Size: 148 x 80 meters, with a height of 2.4 meters for the GLW arches.

Surface Area: Approximately 12,000 square meters, equivalent to two football fields.

Weight: 400 tons of wood, with a central steel joint weighing 800 kilograms.

Length: 12 kilometers of membrane, which is equivalent to the distance to the next town.

Logistics: Unusual processes, procedures and transportation solutions for 33m-elements.

The complexity of this project encompassed various segments, resulting in a continuous nine-year process of design, adaptation, and installation. This timeframe can be divided into three general phases, (i) covering the main middle part and partially the round calottes, (ii) completing the calottes, as well as the main entrance, and (iii) adding additional closures, and making changes to construction elements. With the potential for further expansion of the archaeological excavation on this site, there may be future requests to cover new excavation areas. This project has significant potential for further development. Due to its large size and numerous restrictions, it presented considerable challenges, particularly in engineering and installation. Many unusual situations arose, leading to innovative solutions and valuable experience in this specific application. At the time of its construction, the protective structure was one of the largest in this technology, highlighting its importance. Despite the Medijana facility being open to visitors, the project is not yet complete. In the near future, further expansion of the archaeological site is anticipated, along with the acquisition of new data and conclusions through continuous monitoring and evaluation of the behavior of this remarkable membrane structure.

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