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The Wadi Cascade – retaining walls for an iconic landscape feature

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Abstract

Typically seen as merely functional rather than artful elements, retaining walls are often overshadowed by more expressive structures. The design of the Wadi Cascade, a group of waterfalls that topple over entirely constructed caves and 14-meter-high cliffs within King Salman Park in Riyad, take advantage of buttress retaining wall typologies that are the backbone of an ambitious landscape project. Externally buttressed retaining walls have been considered unattractive since the mid-20th century, but in this instance this classic technique is used to express the regional geology of Saudi Arabia and construct extreme earthworks.

The Wadi Cascade aims to reconnect the people of Riyadh with nature and water, taking direct inspiration from the many canyons and other spectacular geological sites to be found on the Arabian Peninsula. The essence of such an artificial feature is to find the right balance between novelty and familiarity. The architectural and engineering response was thus to use flat, folded reinforced concrete surfaces, strengthened by counterforts. The outer faces are covered by natural stone masonry of varying depths laid to resemble both the stratified geological formations of the region and traditional dry-stone walls.

This paper describes the genesis of the project and its development in terms of reinforced concrete design and stone facing. Computational design techniques are demonstrated through the full integration of BIM and the import of 3D data into the structural analysis software.

Keywords: retaining walls, Computational design, structural design

1. Introduction

The present paper presents the multidisciplinary design of the Wadi Cascade, an asset within King Salman Park. The park is currently under construction in the center of Riyadh, Saudi Arabia. Within the park, the task was to create a forested park within which a network of experiences, constructed natural spectacles, gardens, and civic institutions would delight visitors. The Wadi Cascade, a group of waterfalls that spill over a constructed cave, was conceived as the central fantasy of nature within the park.

Figure 1 - "A fantasy of Nature": the initial render – credits : Squint Opera,MVVA

By definition, a fantasy is something believed to be impossible or unattainable (Figure *1*). There is likely no more fanciful thought or deeper desire in the desert landscape than abundant water, and on a project site that is almost perfectly flat, the extreme cliffs of the Wadi Cascade only heighten the effect. There is no sense in which a waterfall could be seen as an interpretation of a local reference. It is the opposite: an invention of an experience that was missing, something novel and unexpected. The design of the cave therefore would be disingenuous if it tried to simply imitate nature—a unique character had to be invented with reference both to local geological formations (Figure *2*) but also to the reality that it would be a highly constructed feature within the park.

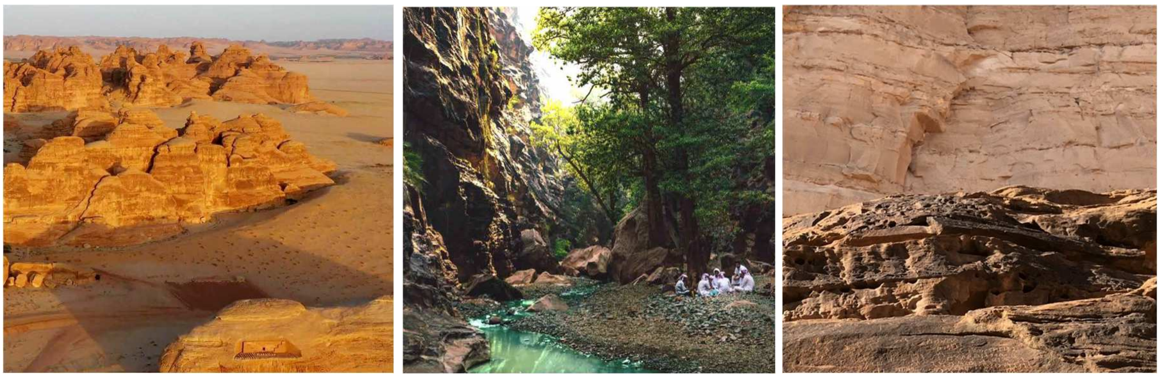

Figure 2 - Saudi geology: Al Hijr (left),Wadi Lajab (middle), Al'Ula (right)

2. The Architectural and Engineering Solution

Acknowledging that the form of the Wadi Cascade should reflect its constructedness meant that the design had to be anchored in something essential about the structural systems behind the surface. Early design iterations would pose the questions on:

- How to relate some freedom of the external faces of a "fantasy of nature" and the regularity of civil engineering structures for level differences around 15 meters?
- How to use concrete to bear the imprint of local soils and geology, such as earth cast concrete panels?
- How to use natural stone for the finished surface without making it look too engineered?

Figure 3 - First iterations: concrete caissons (left) – earth cast panels (right)

Each approach (Figure *3*) had different implications on the presentation of a surface material that would be seen as the Wadi Cascade cliff and cave surfaces. Additionally, the cluster of waterfalls and other water features required mechanical rooms that would need to be hidden within the structure, which made systems that created cavities within the structure advantageous.

The canyon-like geometry resulted in significant differences in terrain levels, up to 14 meters high. This rather uncommon height requires the design of specific retaining earth systems.

In general, the design of retaining walls consists in two main interrelated aspects:

- External stability: making sure that the structural system is balanced in regard to lateral earth pressure.
- Internal stability: giving dimensions for the structural elements to make sure they resist bending and shear generated by lateral earth pressure.

As the footings of retaining walls are located on the limestone bedrock, the external stability is mainly controlled by the width of the footings.

The original concept of the Wadi Cascade design aims at taking advantage of the structures needed for internal stability to give the artificial canyon its desired shape. To be able to withstand the bending and shear created by lateral earth pressure, one may design wall sections which follow the bending moment diagram. In the case of lateral earth pressure, the need for stronger structural sections is at the bottom of the walls, while the top is where material is minimal. Therefore, a solution could have been a cantilever wall, thicker at the base and tapered as one goes up. However, this typology is material consuming for heights over 10 m.

On the other hand, counterfort or buttress wall systems are stronger and help save a large amount of concrete. These structures have concrete webs perpendicular to the stem that add flexural resistance to the retaining system. Instead of defining the classical triangular shape of counterforts or buttresses, the design team decided to define steps whose width increase proportionally to earth pressure, which in turn increases with depth. When this profile is extruded along the wall and covered with stone coursing or textured concrete, the result is an evocation of geological layers.

Consequently, this concept was applied in an erratic way to get closer to more natural shapes (Figure *4*).

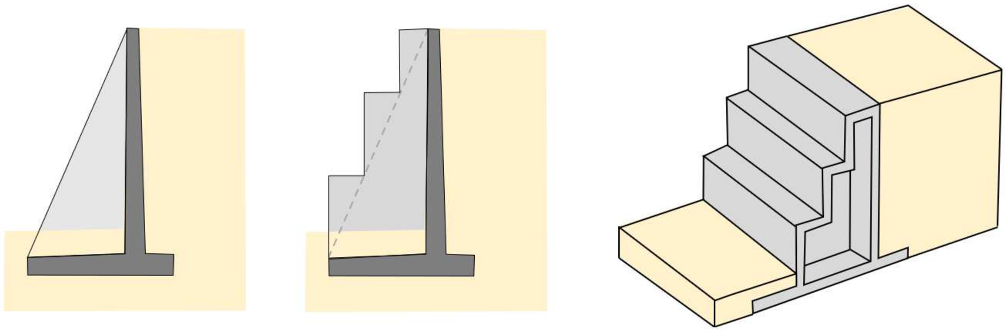

Figure 4 - Typical cantilever retaining walls with buttresses / External shape of buttresses with steps at Wadi Cascade/ Extrusion of the shape to define the three-dimensional concept

Therefore, when the overall geometry of the canyon faces tapers, the structural system consists in retaining walls with buttresses. Where the canyon façade is rather vertical, strengthening of walls is done behind the stone coursing, with counterforts. To reduce the resulting complexity of the concrete formwork, these counterfort walls are rectangular. Since the waterfall's slab presents a large cantilever with respect to the stem, the counterfort walls are extended inside the canyon, to act as cantilever supports (Figure *5*)

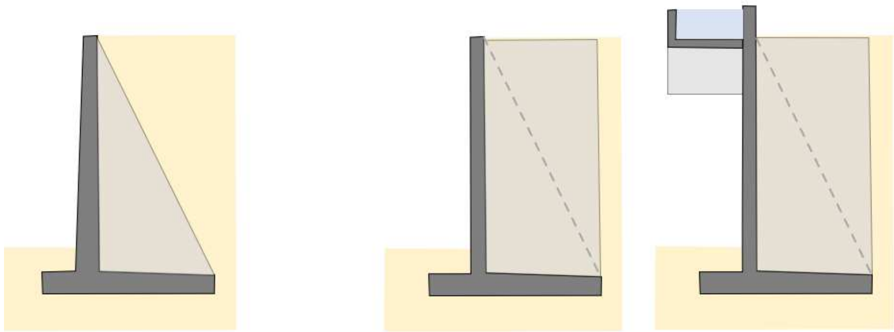

Figure 5 - Typical cantilever retaining walls with counterforts / Wadi cascade retaining walls with vertical counterforts / Extension of counterforts walls to act as cantilevers, in blue: water basins.

The general layout of the walls is random: while the spacing between the buttresses or counterforts is around 3.5 m, the angle between the wall planes is variable, so as to create a folded façade, the accidents of which are familiar in some way with the geological forms of the region. A typical 30 cm front wall strengthen with 45 cm thick counterfort or buttresses is arranged to withstand pressure at the maximum height.

Finally, the concrete structures are covered with mainly natural stone, laid by horizontal strips, and some precast textured concrete elements (Figure *6*). The scale of these details breaks up the large-scale effect of the walls, and once again strongly evokes the natural cliffs while acknowledging the artificial nature of the construction (Figure *7*).

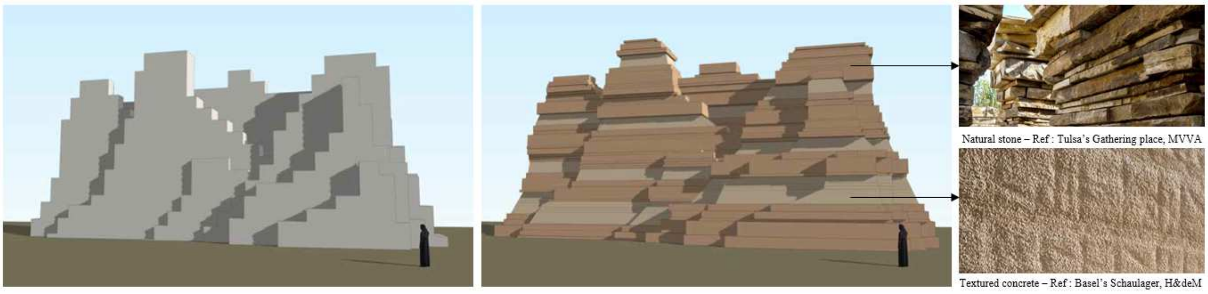

Figure 6 - Reinforced Concrete structure (left) – Coursing of finish materials (right)

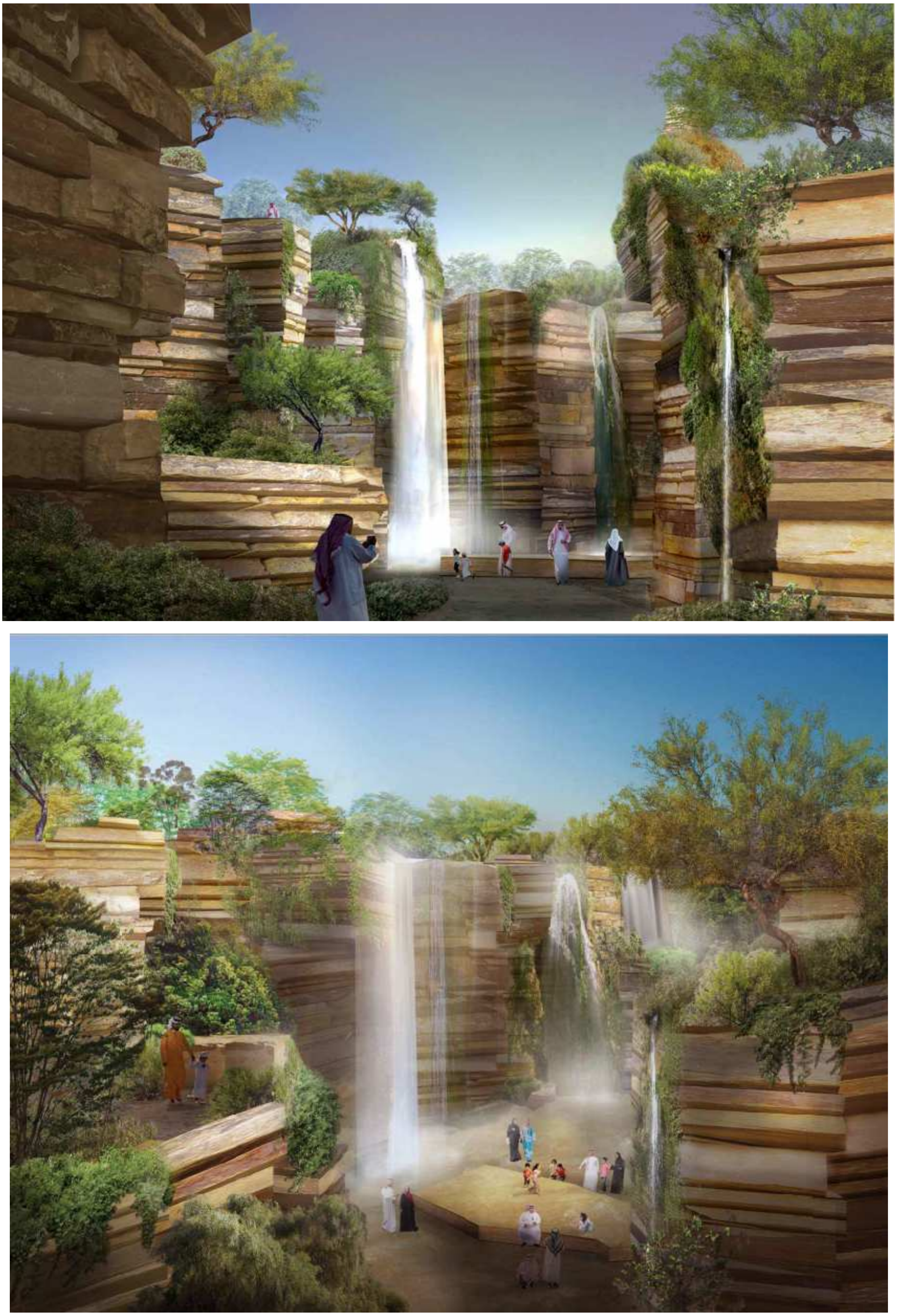

Figure 7 - Renders of the Wadi Cascade project – credits: MVVA

3. Structural Design Development

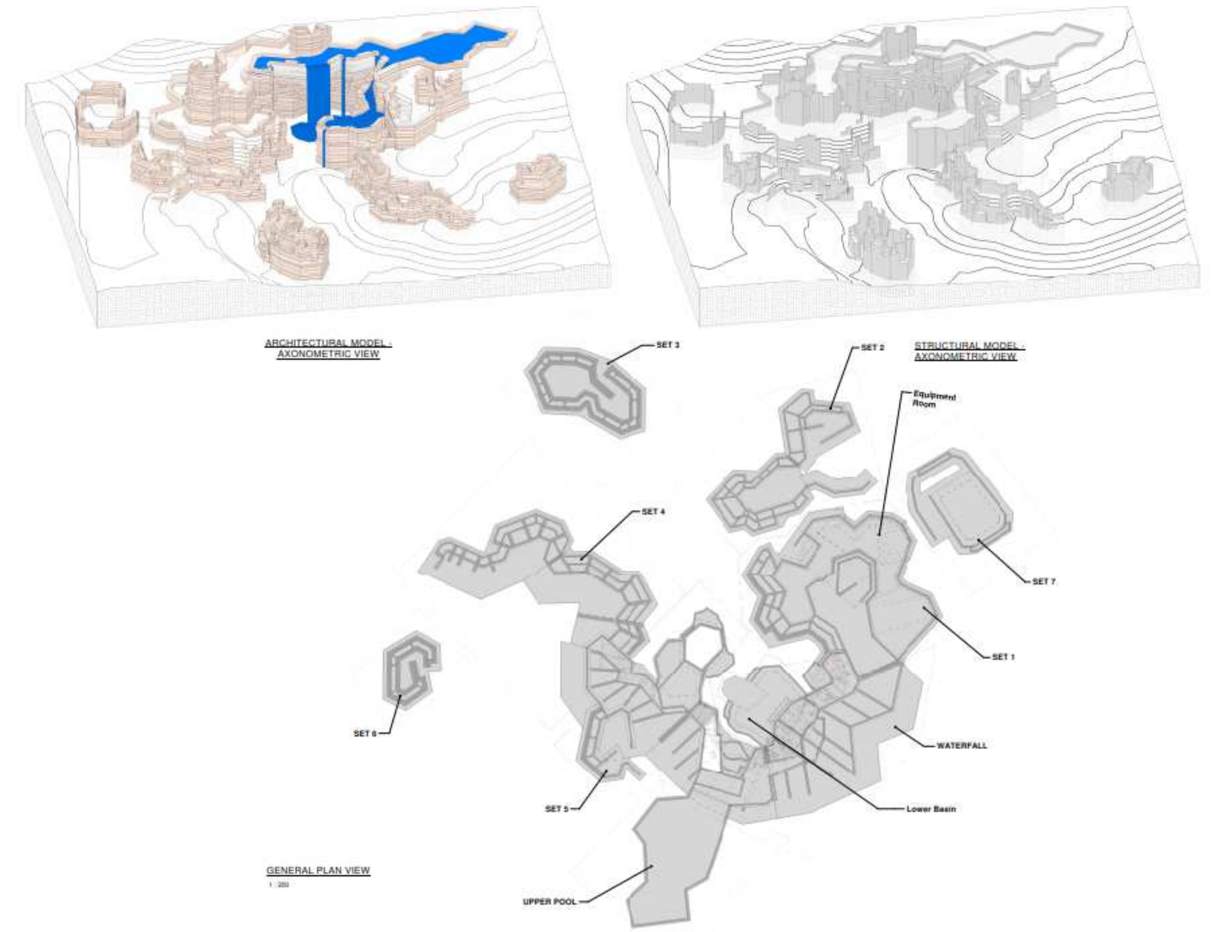

Figure 8 - Axonometric view with coursing and basins (top left), Axonometric view of structure (top right), plan view of structure (bottom)

The structural design of the structure was conducted in four main phases.

The first phase was the genesis, a work where architectural and structural debates led to the first drawings and to the typologies to be used (as explained in the previous section). During this development, some planted terraces and belvederes were designed by the landscape architect in the shape of a multi-storey tower. The engineering team chose to make the overall shape hollow to avoid the creation of earth-filled silos. The empty structure could then be used to house the waterfall pump room (see « equipment room » in « set 1 » in Figure *8*). Moreover, this strategy avoided the need for excavation and a buried structure, whose integration into the landscape and technical project was complicated. The other “sets” of the structure were defined as per the concepts described earlier. Terraces were then arranged with a minimum of 2.5 m thick layer of topsoil. The entire structural project was developed to disappear behind the stone coursing in order to respect the landscape project.

From there, the second phase of development consisted of 2D calculations of all elements. For the walls, the geometry was governed by external stability checks. Mainly, overturning and sliding of the walls were prevented and the bearing capacity of the founding limestone or backfill was ensured.

At first, a "no joint" strategy was considered on all sets. However, the important spans in some sets like the "main waterfall" would have demanded a non-linear analysis of concrete which would have resulted in important reinforcement sections of steel. For these reasons, expansion and contraction joints were strategically placed instead, and minimal shrinkage and temperature reinforcement was ensured in all sections.

The third phase was a closed loop between a 3D, BIM, and FEA model (Figure 9). The architects were responsible for the 3D design, which was created using "Rhinoceros 3D" software. The structural engineers then used this 3D to transform it into a BIM model in which geometry and materials were detailed and refined (Figure 10). This was done using "Autodesk Revit" software. Finally, this BIM model was used as the skeleton for the finite element model of the two most complicated sets of the Wadi. These FEA models were used to check all the previously done and simplistic 2D analyses.

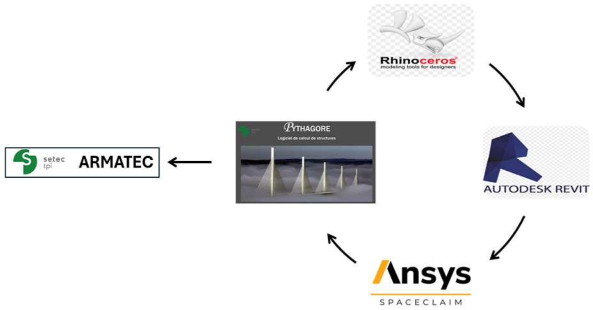

Figure 9 - Softwares used throughout the structural workflow loop.

The transfer of the realistic representation of the Cascade from "Revit" to "Pythagore", setec tpi's in house FE analysis software was made possible by "Ansys Spaceclaim". It is a software that was mainly used to guarantee the connection between all the plates before meshing them and loading them into "Pythagore" (Figure 11). This process formed a loop, as the outcomes of the FE analysis prompted modifications and iterations within it. This enabled us to identify areas where simplistic approaches were no longer relevant. This was particularly true at the borders of the different sets, where stress concentration was sometimes observed. An important optimization was the width of the slab foundation that was reduced where possible. Once the geometry was locked, internal stability was checked using both "Pythagore" and "Armatec", another setec tpi in-house software, whose main purpose is to calculate maps of reinforcement on all fibers of concrete shell elements.

For the structural calculations, the FEA model was loaded with all the dead loads, live loads and earth lateral pressures that are to be expected on the waterfall. Stresses were then checked against regulatory materials' limits in "Pythagore". Afterwards, "Armatec" was used to determine the horizontal, vertical and shear steel reinforcement bars. The use of this loop system from an internal stability point of view allowed the formation of several zones that were similarly reinforced. This also reduced the number of plans and details required to describe the project, resulting in simpler on-site execution.

Once phase 3 was concluded, the fourth and final phase was finalized: the formwork and reinforcement plans.

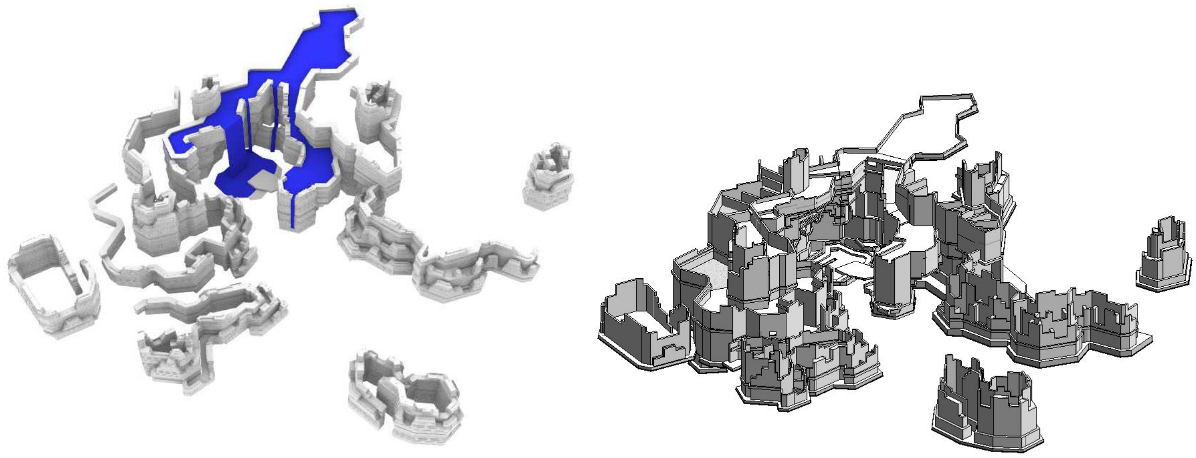

Figure 10 - Rhinoceros 3D model (left) – Revit BIM model (right) – credits: setec tpi

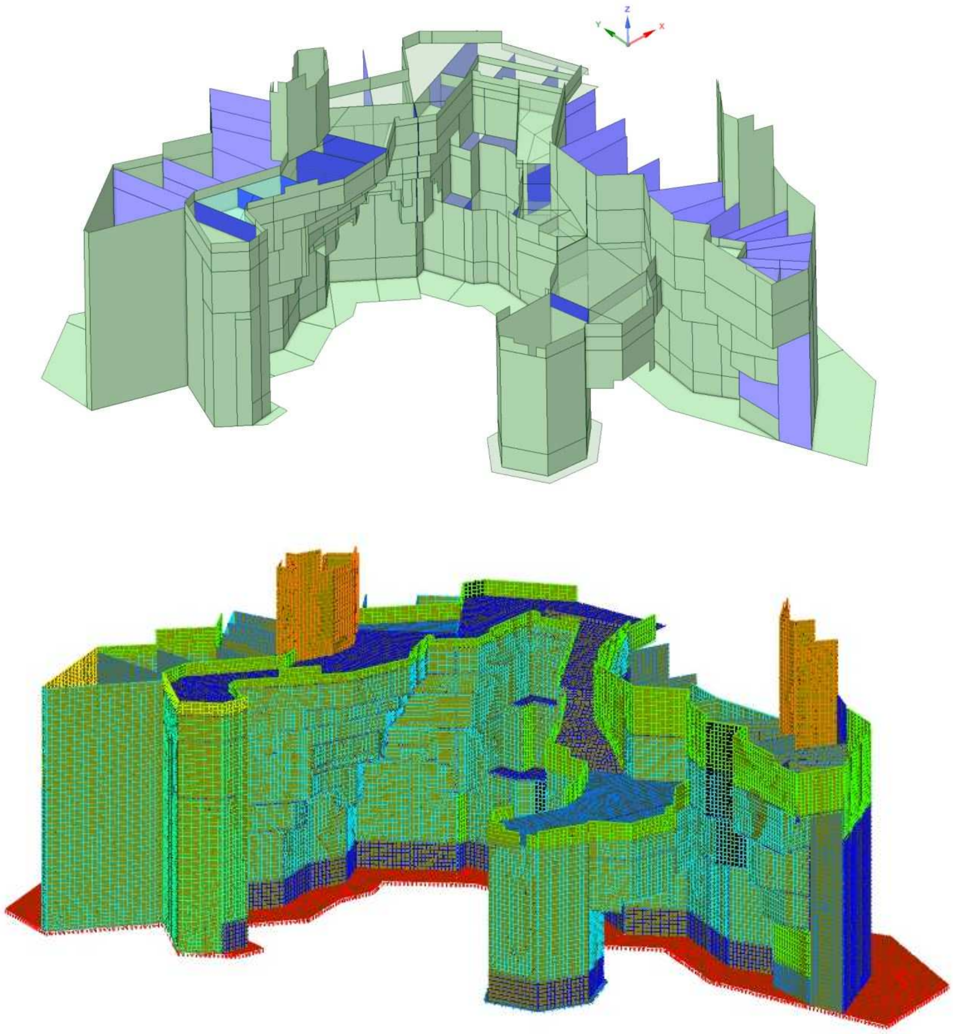

Figure 11 - Spaceclaim - 3D Geometry (top) - Pythagore - Finite Elements 3D Model (bottom) – credits: setec tpi

4. Stone Façade Design Development

The large pieces of sandstone masonry to the nearly vertical walls of the cascade have undulations in the face large projections, stone copings to the top of the walls and changes in direction. These conditions presented challenges when developing preparing the anchor fixing and supporting details system concept design. Once constructed, the stone must have the appearance of a natural rock face.

The stone fixing detailing involved setting geometrical rules ensuring the stone wall's complex geometry constructability while rationalizing as much as possible the concrete supporting structure's own geometry. These rules included maximum stone sizes, overhang between rows, self-supporting masonry height, etc.

The design of the fixing anchors respects the aesthetic requirements considering the weight of the sandstone masonry units and the challenges of the stone masons during installation (Figure 12).

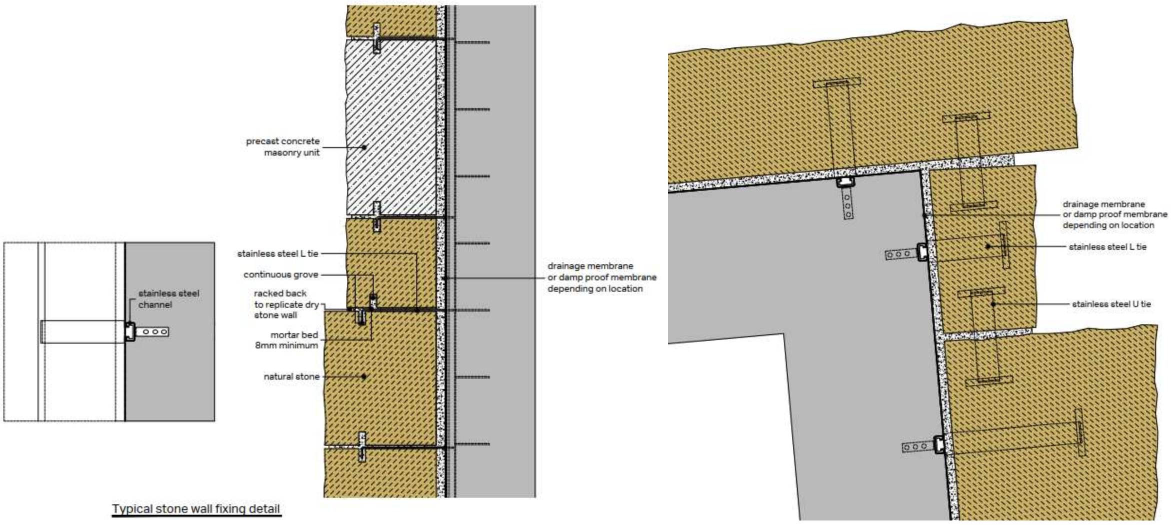

Figure 12 - typical stone wall fixing detail (left) – typica open corner detail – horizontal section (right) – credits: MFS

The anchors are designed to ensure restraint against the overturning moment of the large sandstone masonry slabs, and to cope with the differential movement between the sandstone masonry units and the concrete backing structure. All masonry units will be restrained with anchors located in the top bed.

Large overhangs are designed as suspended precast concrete elements with embedded natural stone finish.

At regular intervals and above large overhangs, the sandstone masonry sits on concrete or large support angles designed to support the stones loads with limited deflection. Secondary steelwork forms part of the anchoring and support systems to manage the most complex conditions such as archways (Figure 13).

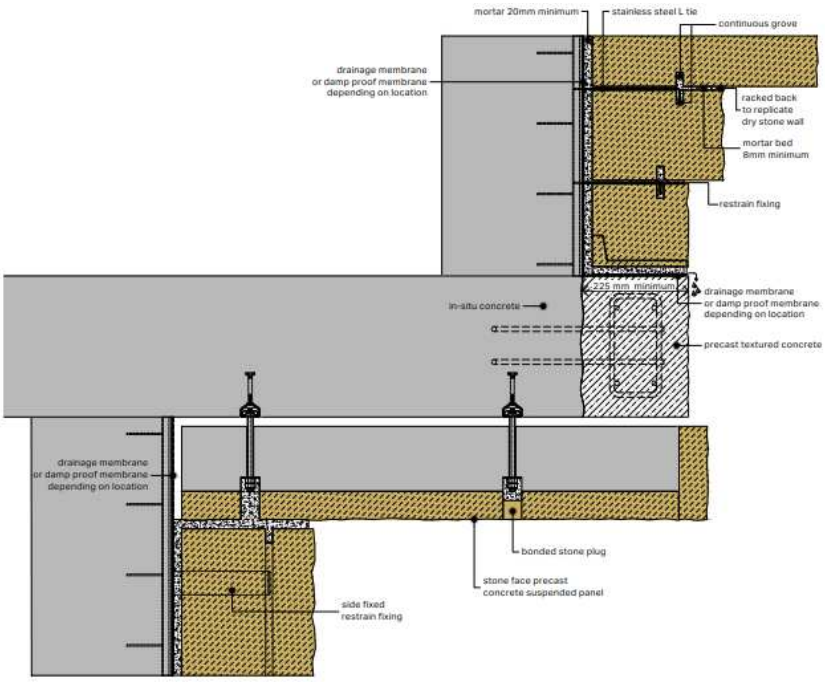

Figure 13 - soffit stone detail - vertical section– credits: MFS

5. Collaborative design

The management and coordination framework included a variety of multi-level planning tools and coordination systems to ensure the proper merging in detail and on-time execution of the project. This section outlines the use of project and design management tools, as well as the selection of collaboration tools in the form of BIM 360 and CAD.

An integrated design process between structural engineers and designers has been created through the use of BIM360. As mentioned earlier, the designers initially designed the façade and water features in Rhino. These designs were then transferred to BIM360, and the structural design elements were based on the internal boundaries of this shell. The design changes made to the structural elements were reviewed in the BIM360 environment, and optimizations were made collaboratively.

Weekly coordination meetings served as a forum for the project team to discuss progress, address challenges, and align on forthcoming tasks. The regular cadence of these meetings ensured that all team members were informed of the latest developments and that any issues were promptly addressed, maintaining continuous momentum and facilitating proactive management of the project. In addition, Asana has been used by project managers to create project timelines, task lists, milestone reviews, and coordination.

Conclusion

The construction of the Wadi Cascade is now under way (Figure 14): concrete structures are built with traditional formworks, attention being paid to the interface of the stone fixing and the concrete faces.

Figure 14- Construction site of the Wadi Cascade – credits: setec

Acknowledgements

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