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CAISSON WELL BASED STABILITY OF ANCIENT MASONRY

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Abstract **: The secular equilibrium at ground interaction is the absolute fact that holds the urban cultural heritage to next generations. "Water" is an indispensable requirement and also a great threat for the shelters of humanity. Destructive effects are inevitable for porous materials while in contact with groundwater. Common design strategy both used in Byzantine and Ottoman Era Architecture oriented on balancing of ground water with caisson wells. Even so, in the Post-Industrial Revolution Period, new water supply technologies developed and ancient infrastructures disabled cause of redundant perception. As a result of the system's inactivity, the variable amount of water content effects the soil strength in two ways: loss of shear resistance and increase of pore water pressure. That conditions lead to deformations in proportion with material tolerances and structural strength limits. In this context, relative model that makes the problematic visible strategically is an important need for documentation of ancient construction technique and protection of the system.**

Keywords **–** Caisson Well, Underground Water, Masonry Structure Behavior, Byzantine Architecture, Ottoman Architecture

I. INTRODUCTION

This work; focuses on theorizing the problem with the the argument that risk potentials linked to water are governed by caisson wells. Aim of this study is to instrumentalise the structural damage detection method related to the urban hydraulic equipment renewal. The motion of the water is subjected to physical forces so the water cycle process is not a kind of random act. On the other hand, the interaction of structural compositions with water includes incidental multi-component reactions. Due to the hyperstatical nature of the masonry system the results may be unpredictable.

Analysis of masonry structures can only be possible by defining the symbiotic relationship established with ground. At this point, variables regarding the physical potentials affect the result. With only numerical performance models, it is impossible to understand the process and manage the potential risks. This situation requires a method for damage assessment that can evaluate environmental data and internal dynamics together. Through the algorithm; "fuzzy logic", inputs and outputs are interpreted in a definite set theory. Exactly, it would be possible to disclose repeated deformations in a random appearance. Thus, the structural variables in the process have been identified and used to describe the dynamic behavior related to underground water.

II. WATER MOTION CHARACTERISTICS AND WELL HYDRAULICS

The basic components of the Earth are air, water and soil. In the hydrological cycle, water circulates continuously in liquid and gas phases, between the atmosphere and the ground layer. The progression of water in rigid blocks depends on the materials porosity; related to the particles pore ratio.

Porosity is a function of the size of the molecule carried by the passages connecting the pores. The size of the transported molecule with larger diameter than the pore passages limits the porosity according to the molecule [1]. The movement of the water from the ground to the atmosphere in the hydraulic cycle against the gravity can be explained by the pressure differences in the pore passages. Capillary water rise and vapor diffusion form dynamic variable water presence in the ground. Because of pore water pressure shear resistance reduces. Capillary water rises from the saturated region to the dry region [2]. In this equation, the water table is the balance surface of the water nappe press with the atmospheric pressure [3].

The level of groundwater can change due to the pressure differences caused by daily and seasonal temperature cycles or the water table feeding by surface water resources. The balance in the ground-building interaction depends on toleration to the changes in the level of the water table. At this point, the primary role that the caisson well undergoes in drainage is balance-oriented. Water table level falls off by catchment of well. This will cause to a pressure decrease inside the well. On the other hand, surrounding formation keeps initial pressure. This pressure difference causes the water to flow into the well from the formation. The water-bearing aquifer does not release water it carries to the well suddenly. Due to the pressure difference, surrounding water leaks into the well [4]. A well cross to the water table in terms of depth, while it reaches above the ground level by a pump base. Thus, the tension of the pressed air is also blocked by this ventilation solution. Air flow provided by the well is supported with galleries in many structures. Connected wells and galleries have a stabilizing effect on the heterogeneous formations. By this way, excessive rising of underground water level could be prevented.

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The decrease of the groundwater level also causes indirectly deformations. On soft grounded foundation bases, wooden piles were used in order to strengthen the ground. Timber components that are constantly in water are subject to deterioration as a result of water withdrawal. As a solution, wells are dug lower than the phreatic layer, inside the impervious substrate, thus creating a kind of underground cistern with an extra storage, in case where the water table would be low, at the end of the dry season [5]. By the water flow that the well provided, timber building components haven't affected negatively by the decrease of water table. Eventually, optimization of any changes that can occur owing to water cycle could be controlled by wells.

Finally, one of the most important function of the wells depends on its use during earthquakes in order to manage the ground safety stress. As a result of earthquake's energy discharge, wave propagation occurs in different types at different frequencies. Water is a kind of set for the propagation of some wave types. The beneficial effect of underground water is damping the seismic waves. As S wave propagates, it shears the rocks sideways at right angles to the load direction. If a liquid is sheared sideways or twisted, it will not spring back. So, the S waves cannot propagate in the liquid parts of the Earth and their amplitude is significantly reduced in liquefied soil [6]. Deceleration of the sudden movement of the water level and drainage of excess water through the wells provides rigid profile.

III. CAISSON WELL SUPPORTED MASONRY STRUCTURES IN ISTANBUL URBAN ARCHEOLOGY

Extant Byzantine and Ottoman Era Cultural Heritage point to developed theories and structural practices against water. From the entire urban archeology, meta analyzes are obtained in terms of qualitative and quantitative diversity based on wells. For instance, it is not possible to find a homogeneous soil profile in all over the nature. The variable density of water presence makes the soil heterogeneous and tending to subsidence. In such cases, the wells provide equilibrium conditions and therefore a homogeneous soil profile.

From a chronological point of view, a particular detail of Hagia Sophia reflects this practice primarily. 2015 excavation data [7] reflect excess water at the session area of structure's western pillars. That is amazingly documented in another early period as a spring source feeding cistern under the apse [8]. In these heterogeneous conditions; structure dynamic behavior is inevitable to deviate from the vertical contour by ground settlement. A damage recorded initially in 558 is related to 20° vertical bending of the meridian section of the dome because of subsidence [9]. Structure is carefully preserved in all era, it has repaired and reinforced after heavy deformations. In the 13th century Byzantine restorations as a solution to the subjected problem, there are four pillars placed on this axis [10]. Thus, the lateral forces created by the weight of the dome are balanced by pillars. The wells in the shafts of these pillars strengthen the elements by collecting the water of located area (e.g. Fig. 1). Current archaeological excavation reports [11] indicate that these two wells were filled with stone and padding material in 1981 as a precaution against moisture. Purely, existing capillarity effects reflect that this intervention has resulted contrary.

M1 Hagia Sophia Church (Hagia Sophia Museum)

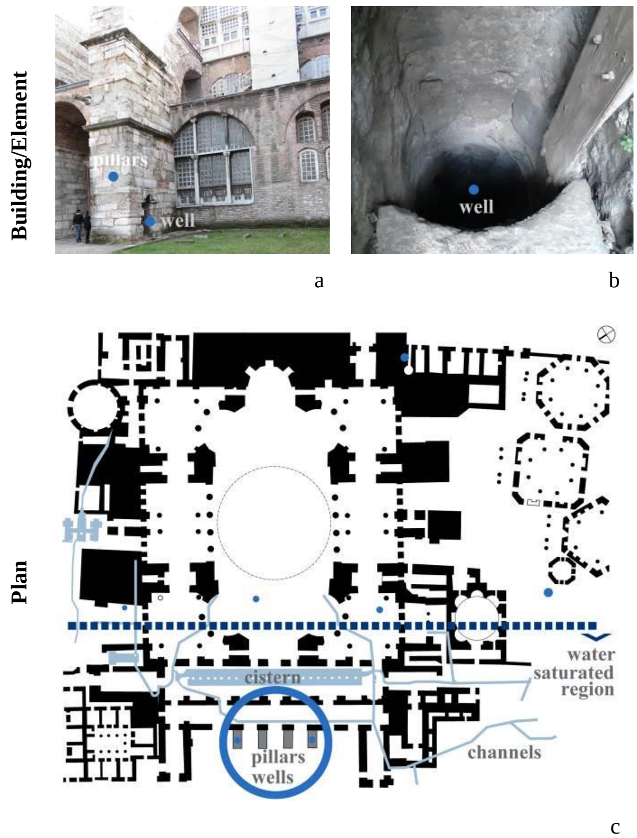

Fig. 1 Usage of well in heterogeneous profile. Survey: [12]

The drainage function of the well is based on the water movement from the ground formation to the well due to the pressure difference. Therefore, there are numerous practice models where the well is situated under the gravity center of the structure or dome origin to balance the loads (e.g. Fig. 2).

In Sergios Bachos Church (Little Hagia Sophia Mosque), which is located about 20m away from the Marmara Sea Walls on the shore line; on the grounds available for liquefaction there is a sample of well usage. Up to 1980, well and pump's presence is visible in documentary [13]. Today there is only visual representation of them. In the asymmetric plan solution, the position of the well corresponds to the center of gravity. The water supply method of the well kept separate from the facility where the surface water collected through the channels that reflecting the resource as a spring [14]. Channels also provided moving drainage scheme had been established within the building, thus, static of water was eliminated. By the inactivated period of caisson well current capillary effects confirm the water presence.

Similar use of the well is to prevent the bending motion of high structures. In San Paolo Church (Arabian Mosque) bell tower block's stability supported by centered well. Although the original form of the well has disappeared, there is still noticeable remain and it is referred in relevant documents [15]. Another well which was added during the Ottoman Period, was found in the narthex and it is still activated.

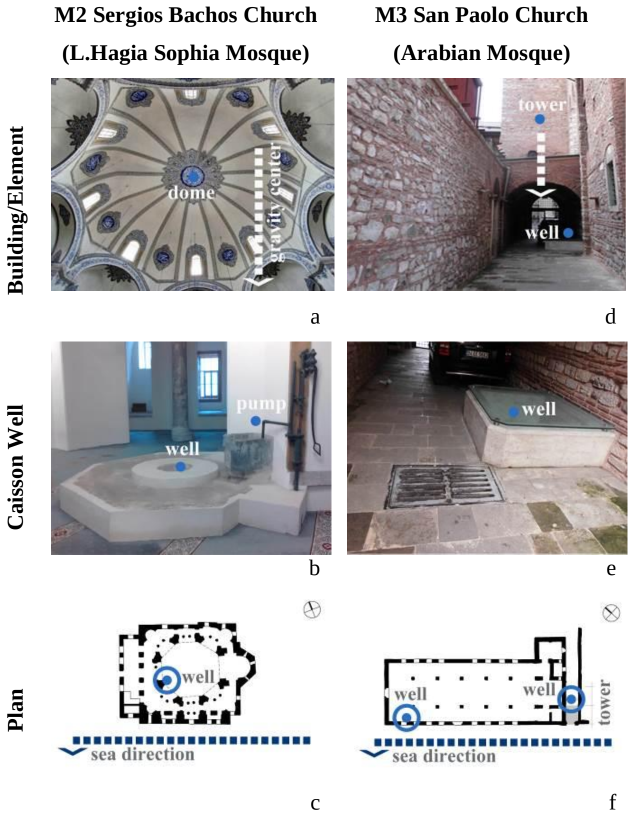

Fig. 2 Usage of well in gravity center of blocks. Survey: [15], [16]

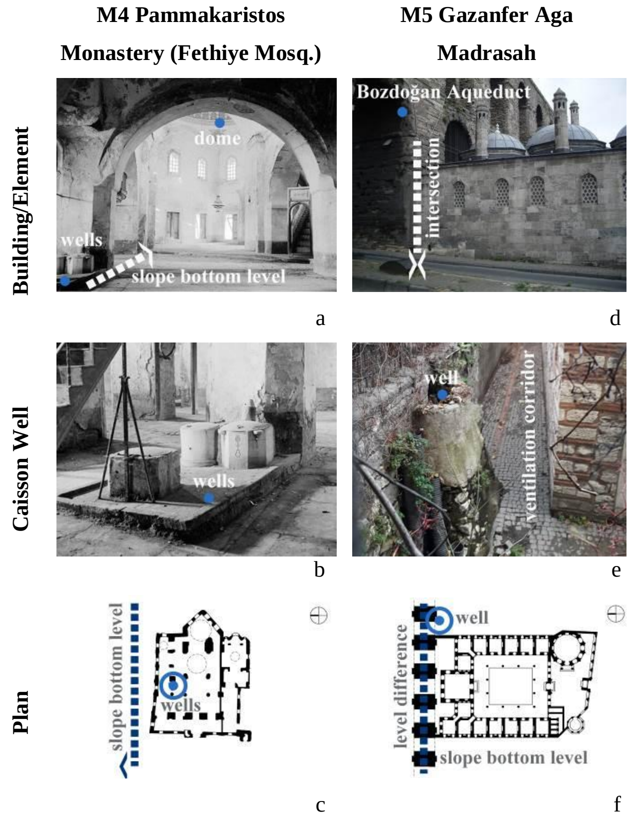

Fig. 3 Usage of well in slope terrains. Survey + M4 Photo: [18], [19], [20]

In world's different geographical location, another high-rise building; Pisa Tower last ground intervention evokes adapted usage of the practice. As a matter of fact, water table at southern of the foundation area is higher than that at north, so that the net result of the underpressure on the Tower is a small stabilizing moment. During intense rainfall events the two levels tend to equalize, thus producing a small overturning moment on the monument; it is believed that the cumulative effects by ratchetting of these repeated impulses has been one of the factors producing the steady increase of inclination in the long term. As a final intervention, a drainage system based on wells and channels was thus installed essentially aimed at stabilizing the groundwater level in the vicinity of the Tower [17].

Another practice model where slope water is collected in terrains is seen in both era. This cause occurs because the water leaking from the surface coincides with a cohesive and impermeable layer. Stepping of the topography in sloping terrain could be possible with cisterns or retaining walls (e.g. Fig. 3). For instance; Pammakaristos Monastery (Fethiye Mosque) was built on the slope of V. Hill which leads to Golden Horn. Slope water discharged to a cistern and stored there. The cistern was designed to be integrated with 3 wells.

Similarly, in Gazanfer Aga Madrasah, the source of the problem is based on the height difference in levels between the Bozdoğan Aqueduct and the structure. Gallery and a ventilation corridor organized at intersection of structures as to release moisture. The well located adjacent to the set wall collects the slope water.

Furthermore, the well breaks the hydrostatic pressure impact of pore water which will form underneath the ground level. Due to the topographical position, Istanbul was considered as "Seven Hilled City" and there are precious monumental structures on each hill set on cisterns. By these substructures topography was stepped and differential settlings of the footings was avoided. Also, a homogeneous seismic base formed under the buildings. The cistern is exactly an underground tank filled with discharged water. In these conditions, caisson wells are a solution to balance inner and external pressure. And a way to prevent flooding of collected water. Just like as the practice in the Nur-u Osmaniye Mosque, at II. Hill of Historical Peninsula. Here, a basement is formed; several cistern rooms organized as a part of foundation. As to discharge pressure of this underground space ventilation grilles are left and a well added.

Except these, courtyards are the inner ranges that have required water management (e.g. Fig. 4). Rüstem Pasha Caravansary is a Coastal structure, where the well is located on the narrow side of the courtyard, close to the sea. Another building on the shore is Şemsi Pasha Complex. In plan layout it is seen that L-plan block madrasah limits the courtyard and the mosque block is positioned parallel to the bisector of the madrasah. In this unusual asymmetrical order well is located on the gravity center of the blocks in the courtyard.

All of these buildings point to a conscious approach for drainage. Lack of knowledge in the interpretation of the building construction methods and details during intervention may lead to incorrect intervention and long-term harmful effects on the structure.

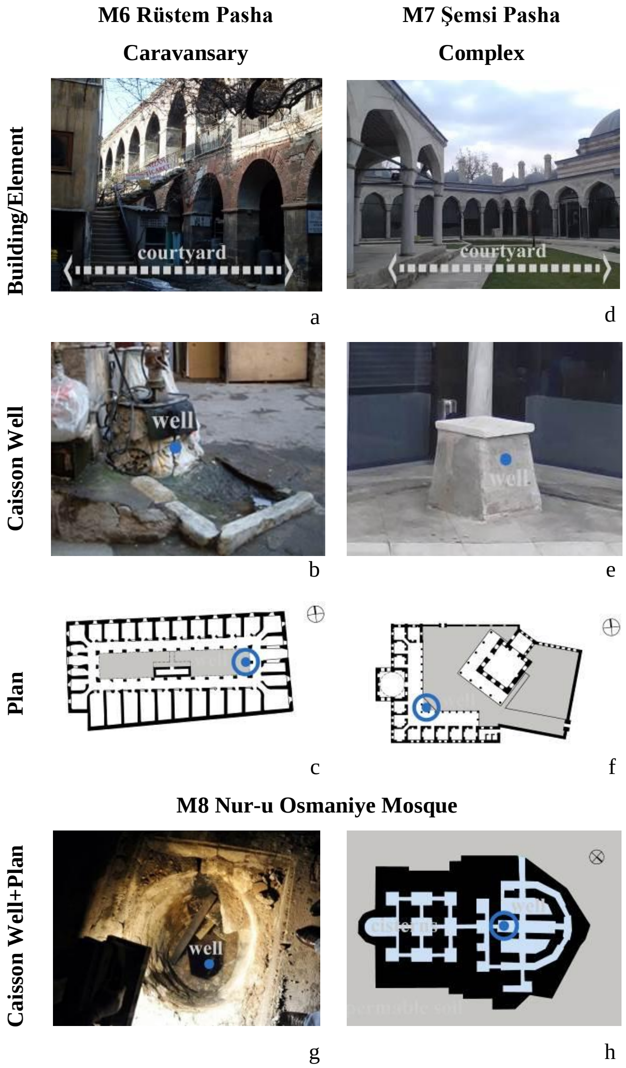

Fig. 4 Usage of well in courtyards and basement. Survey: [21] [22]

IV. EVOLUTION OF DEFORMATIONS OCCURRING DUE TO UNDERGROUND WATER

As to sustain drainage function of the caisson well, it has to be kept active by regular groundwater extraction. This attribute is already exists in Cultural History of Turkey. This case has an adjective with local terms like “bogalık” or “din” to characterize deactivated wells [23]. Because of system’s inactivity the water content of the soil changes and due to the nature of masonry variable amount of deformation occurs.

On the other hand, at analysis phase, the cause of structural deteriorations cannot be reduced to single reason. Damage indicators with the same visual effect can be different sourced deteriorations. Only with collaboration of architects, geotechnical-civil engineers, through observations, laboratory analyzes, dynamic calculations clarifying of conclusions and diagnoses could be possible. In other respect; repetitive, definable damage types under the same conditions form predictable indicators. Water-related deterioration varies across the physical properties of the material. The brittle nature of the stone determines the elastic strength of the structure under shear stresses due to settlement.

If the ground is not strong and homogeneous enough to bear the loads, decay and eventually damage will occur. Soil and foundation settlement result with torsion, bending and shear motions. The most significant damage indicator reflects to the superstructure is shear cracks. According to the type of settlement, convex and concave or in one direction bending take place. Shear stress increases in regions where chipping cavities exist in the wall. If this tension exceeds the tensile strength limit of the masonry material, cracks occur. Cutting cracks are formed by forces depending on the direction where resultant function affects.

If the strength of the wall construction components or binder is weak, it will cause the material to crushing and rupture. Crushing on the walls and pillars reveals itself with numerous cracks in close proximity to the basement [24]. In addition, the dissolving of the mortar content by water may result with joint outflow. Thus, shear stress occurs between the blocks. In this case, binder crushing can also exist.

Furthermore, the porosity and the water absorption capacity of the material make it vulnerable to the physical/chemical reactions that the water will trigger. For example, phase changes of the wetting-drying process can result in material loosening and weakening. The cause of the deformation, known as the frost effect, depends on the periodic volume changes. In the freeze-melt cycle, ice can crystallize and the salts penetrate in the pores and erode the material with the volume difference. In addition, solutes which determine the water purity and degree of freezing effects tension [25]. Material may split as a result of expansion. Because of water vapor, pressure differences may occur between the structural element section and the environment. The pressure differentials are compensated by the phase transition of the water vapor. The condensation water collected in this way causes distension of the construction elements.

Changes reform in the atomic structure of the material as the minerals in the stone composition react with the water. Loss of material becomes apparent in the form of decomposition in layers. Salt, which is transported by water or contained in construction materials, can cause erosion in materials and color change in pigments. Waterborne salts can move only as dissolved substances. When water evaporates, any dissolved salts remain behind. Crystals of salts such as potassium and sodium sulphate are a common sight on walls, especially in the summer months [26].

All these deformations interact with biological degradations by providing suitable living environments for plants and organisms. With capillary water movement, the necessary nutrient needs are transported. The plant roots movement in the wall section in order to find water can lead to deterioration such as cracking, explosion and fragmentation. Due to the coating of the wall surface with algae, the lack of air causes hazards. And also, the fungal species present in nature are numerous and ubiquitous. Their development is promoted by conditions of high relative humidity, and air temperature between 18°C and 32°C; for this reason, they are very abundant in damp buildings [27]. Fungal can cause chemical degradation on the internal structure of the material.

As an object of theory, the nodal point of the problem is the correlation between hydraulic equipment and resultant structural modal parameters of masonry structures. In evaluated model buildings, the overlap ratio of the inactivated caissons wells with the damage indicators supports the argument in this respect (e.g. Fig. 5). Eight structures subjected to the model are under different conditions; in M1 (Haghia Sophia), M2 (Sergios Bachos Church) and M4 (Pammakaristos Monastery) well was stuffed with filling and concrete, in M8 (Nur-u Osmaniye Mosque) well was disabled without any capturing, in M3 (San Paolo Church), M5 (Gazanfer Aga Madrasah), M6 (Rüstem Pasha Caravansary), M7(Şemsi Pasha Complex) well is operating as required.

In M1 (Haghia Sophia Church), researchers explain reason of deformations with the ground elasticity module [28]. Furthermore, the macroscopic measurements made on the material samples concur at the same result. The presence of water-soluble harmful salts such as Ca, Na and Mg sulphates and chlorides, causes deterioration of the stone. This type of deterioration occurs due to the effect of the capillary action on the underground water and the movement of the soluble salts. Also, biological attacks started with the stone because of the constantly influential moisture [29]. Current deformations can be perceived with observation from the intersection of structure and the well.

In M2 (Sergios Bachos Church) the capillary water movement around the concrete filled well confirms that it is still fed with the water table. The damages caused by pressurized water which has been documented after well blockage. In 1995 records it was emphasized that groundwater in this region is ponded and may lead to ground liquefaction [30]. In undergoing period, building modal parameters have evolved as predicted. The result of the 2001 report data shows deformations increasing at sea direction, resulted with the inclination of the whole apsis; which is about 40 cm of the wall in front [31]. When the current damage indicators are followed, it can be perceived by observation of water effect mainly on the southern outer walls of the structure and on the surrounding area where the well is located.

In M4 (Pammakaristos Monastery) the 3 well integrated to the cistern was stuffed with filling and concrete. The in-situ data collected in 2017 include deformation concentrated in the center of the dome and in the northern foot. It has been observed that plaster bubbles and salt penetration developed on walls of the north facade, pillars bearing dome under intense humidity. The meridian cracks that descend over the dome windows are joined by sharp horizontal cracks indicating the possibility of ground settlement. Losing the effectiveness of drainage is likely to cause unbalanced loads.

In M8 (Nur-u Osmaniye Mosque) the existing well is described as a guide well in the daily reaching historical documents, and it was discovered after the dismantling of the rubbish-filled rubble in the 2012 period repairs. The current reflections of damage indicators show that physical damage such as algae occurrence, salting, decomposition is partially replicated. Lacking operation in the previous interventions is only to ensure activated usage of the well.

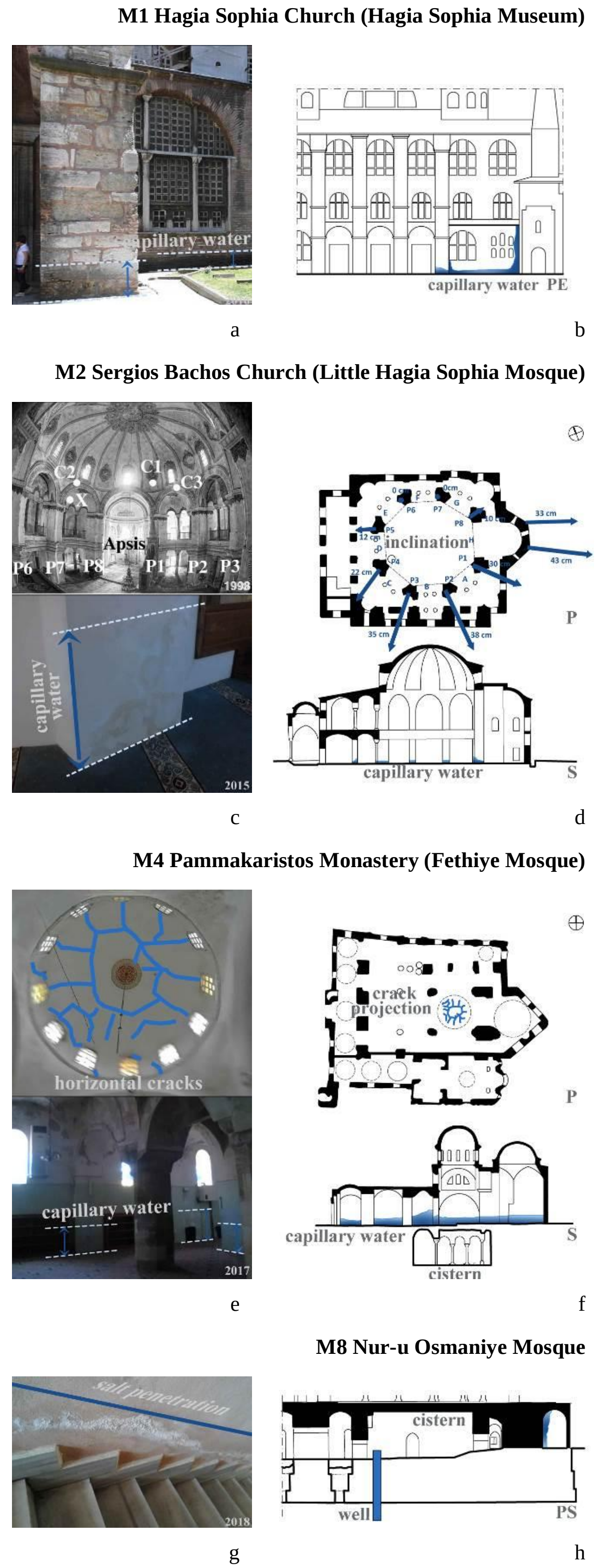

Fig. 5 Deformations observed in model structures.

Survey+ M2 Data: [32], [31], [19], [22]

V. A RELATED MODEL TO EVALUATE ADDITIVE VALUE OF WELLS TO STABILITY

All parameters in connection with infrastructure are a part of collective structural organization so every intervention to the system's operation includes structural modal behavior data. From this perspective, lack of risk management is related to the connivance of qualitative consistent possibilities. On the other hand, parameters that cannot be classified under typologies create comparability difficulties and variability.

In cases where such undefined fields are concerned, there are samples take place in the literature of science history in which general inferences are made with systems that make interval-valued measurements. By means of the algorithm called "fuzzy logic", inputs and outputs can be interpreted in a certain set theory by simplifying them. This control and decision-making method, was introduced in 1960, is frequently used in the field of geographical information systems in which non-linear variables such as climate-precipitation exist [33].

While classical logic works through values and scoring systems, fuzzy logic focuses on the current range and probabilities. The method offers an identical way for evaluating the working principle of the well like assessing the operation of any machine. By interpretation of all data in the order of input set/rule base/output set algorithm, a correlation can be reached that considers the possibilities and fuzzy values despite the uncertain dynamics (e.g. Fig. 6).

For example, a classification like "the rocks near the surface of the bedrock" forms a non-mathematical ensemble, while on the other side the unspecified aspects of the filling layer on the rock, which play a role in the water saturation are identified. Moreover, the influence of inputs on each other is important in terms of reflecting the physics of system. All data interpreted flexibly by transferring to fuzzy matrices.

In the operation of algorithm adapted to research focus, the data base; "input set" consists of values and variables that affect the water saturation. In this respect, settlement morphology, ground profile, and water table level are the three dominant elements of the input set.

The settlement morphology reflects location-based values. There are resources such as rivers, sea water, slope water that feed groundwater depending on building location along the shore, on the slope or on the hill. The ground characteristics reflect how the soil will be affected by existing water resources. The thickness of the permeable layer, hence the depth of the main rock is determinative. And the water table level is accepted as the basic parameters affecting the soil strength in terms of margin to the basement depth. The input parameters are interpreted and processed to graphs corresponding to the (-) or (+) poles to determine the direction that affect to the function.

The rule base used, which carries the findings to the next stage, can be explained with the condition as "whether…. if". The rule base is formed by the well's operated-deactivate-blockage usage options. On the output columns, visual and analytical deformation data are collected for the dynamic behavior of these structures

	I			R	O		C
	Settlement Morphology	Ground Characteristics	Groundwater Level	Well Processing	Physical/chemical Deformations	Mechanical Deformations	Fuzzy Value
M1 Hagia Sophia Church	+	+					
			-	-	-	-	-
M2 Sergios Bachos Church							
	-	-	-	-	-	-	-
M3 San Paolo Church				+	+	+	+
	-	-	-	-			
M4 Pammakaris. Monastery			+				
	-	-		-	-	-	-
M5 Gazanfer Aga Madrasah		+	+	+	+	+	+
	-						
M6 Rüstem Pasha Caravansary				+	+	+	+
	-	-	-				
M7 Şemsi Pasha Complex				+	+	+	+
	-	-	-				
M8 Nur-u Osmaniye Mosque	+		+				
		-		-	-	-	-

Fig. 6 Graphic summary of fuzzy logic evaluation model. I: inputs, R: rule base, O: outputs, C: correlation

From this point, producing the diagnosis could be possible. The structure is scored with a membership indicator (-) if there is deformation indicator, (+) for otherwise. Thus the results have been clarified in terms of fuzzy logic extraction. All the results obtained from the algorithm are in accordance with the rule base, overlapping with each other in terms of output data.

As can be seen in the toolboxes, masonry buildings that have at least one of the existing caisson wells is in active use and exhibits positive performance in terms of stability. In Models 1 and 8, although the input values in the (+) polarity were predominantly influenced by the rule base, the membership class was negative (-). In Model 2 all values are negative, so the membership class is affected by matrices (-) polarity. With a contrary effect, the results were positive despite the input values in the model 6 and 7 is at (-) direction. In Model 3, the rule base is operating both blockage and activated wells.

When algorithm interpreted as a whole it has been observed that building models with input values that facilitate the movement of the water in the ground can have different stability depending on the effective use of the well. This low correlation between inputs and result values inevitably interrogates the hierarchy of variables.

VI. CONCLUSIONS

The effect of water on soil behavior is not only related to the resources, but also in connection with geological and morphological potentials that direct water. This situation, in different positions, on different conditions, comes out against the characteristic of location: like seawater eroding coastal fillings or underground water affecting at different rates on heterogeneous, permeable soils.

Risk management in this interaction-between nature and architecture- is in correlation with dewatering of the ground. It is possible to achieve this balance provided by the wells in the studied structures. For this purpose, the monuments which are located in different reliefs in the urban geography and have different contractors with different power balances are put into fuzzy evaluation algorithm.

In all cases, the deformation patterns and the water control activity provided by the caisson wells yielded parallel sections of work. With this in mind, it has been emphasized that promptly identification and protection of building practice that maintains monuments stability under water is necessary.

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