Climate Change and the Structural Resilience of the Doha Metro

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ABSTRACT

In recent years, the Doha Metro has been the spearhead of Qatar's effort to expand and upgrade its transportation infrastructure. In its current phase it will comprise three lines of an approximate overall length of 76 km and 37 stations. It is self-explanatory that such a significant infrastructure project should be a resilient one. The requirement for a 120 years design life for its permanent civil works structures implies that they should be resilient not only against the current environmental conditions, but also against future conditions due to the ongoing climate change. Resilient means that they will be able to serve their purpose under foreseen climatic changes during their design life. It is expected that climate change will increase the occurrence and intensity of weather events, especially in the Middle East and North Africa region. As per the AR5 assessment report of the Intergovernmental Panel on Climate Change "Climate change will have profound impacts on a broad spectrum of infrastructure systems..." transport being one of them. Furthermore, since transportation is interconnected with the economic and social welfare of an area, it is evident that the metro is a critical infrastructure system of Doha. In this paper, the climate change related main hazards on the Doha Metro permanent assets are presented along with the mitigation measures that have been adopted through provisions in the structural design and the materials used. Furthermore, suggestions for future contingency measures are made.

Keywords: Climate change; Doha metro; Hazards; Resilience; Mitigation

1 INTRODUCTION

The ongoing climate change in the Middle East region is expected to impact the rainfall, the wind, the ambient temperature, the air humidity and the groundwater composition. The risk of climate change becomes more prominent by the considerably long design life of 120 years of the network.

From a structural point of view, resilience means reliability, robustness and durability. Leaving robustness aside (see §3.1) as it is not in the scope of this paper, climate change can affect reliability in terms of loads and durability in terms of deterioration mechanisms. To this end, an assessment of the current resilience level is performed and its results are compared with the possible effects of the expected climate change. At the end, conclusions are made on the resilience of the Doha Metro against expected changes to environmental conditions in its design service life.

2 CLIMATE CHANGE PHENOMENA CONSIDERED

The main civil structure assets of the Doha Metro are underground (Stations, Tunnels), at grade (Stations' Shelters, Depots, Stabling Yards, Troughs) and elevated (Viaducts, Stations). These can be affected by the frequency and intensity of the following phenomena influenced by the climate change:

2.1 Rainfalls / Floods

Changes in precipitation intensities and frequencies significantly influence many design parameters, e.g. groundwater table levels, volume of run-off water, etc. The most important risk associated with increased rainfall is that of flooding of underground civil works. Heavy and intensive rainfalls, in combination with an increasing groundwater table or sea level, can potentially lead to flooding with disproportionate consequences for the serviceability of the affected structures. For this reason, the flooding risk has been thoroughly investigated during the design stage of the Doha Metro, aiming to minimize all associated risks by planning and implementing several "lines-of-defense" (both construction and operational measures, see §3.3).

2.2 Winds

It is expected that climate change will affect the wind intensity around the globe. Winds are generally expected to decline in speed, but storms are expected to bring stronger winds with them as they are "fed" by the warmer air and water of the oceans. Qatar might not be directly exposed to the ocean, but the phenomenon of increased winds during storms cannot be excluded as a remnant of a strong storm, without further research.

2.3 Rising temperatures

The temperature around the globe is rising and so does the sea level. But it does not stop there: scientists all over the world are confident that temperatures will continue to rise in the future. For the Middle East in particular, as per Pal and Eltahir (2015) and Coffel et al., (2017), it is predicted that until the end of the century the temperatures will be rising to levels that the wet-bulb temperature threshold of 35^{o}C will be exceeded several times (compared to none until the date of that study). Moreover, the maximum dry-bulb temperature might reach 60^{o}C in some places (e.g Kuwait City). While most of the Gulf countries are vulnerable to one of the two temperature indexes, Qatar, due to its unique geographical location, is vulnerable to both.

2.4 Humidity

Due to the expected increase of the temperatures in the area, it is expected that the humidity levels in the atmosphere will also rise as increased volumes of water will be evaporating.

2.5 Groundwater composition alteration

It is expected that climate change will increase in the long term the salinity of the sea water due to the increased intensity of the precipitation – evaporation cycle. In addition, increased air pollution due to anthropogenic activities will further burden the groundwater with chemicals through rain. The possible result will be a more aggressive groundwater, with some chemicals (e.g., sulphates and chlorides) present in the form of a solution in the groundwater.

All the above, isolated or combined, might affect the civil works assets of the Doha Metro. Below it is presented how the structural and civil designs and selection of materials are to provide structurally resilient structures against the above phenomena.

3 STRUCTURAL/CIVIL DESIGN PROVISIONS TO ACHIEVE RESILIENCE

For the Doha Metro, Qatar Rail specified a 120 years design life for its permanent structures and the use of the Eurocodes for their design (see Qatar Rail reliability and durability assessment reports). The Eurocodes are in power in many countries within, as well as outside, the European Union. They emphasize on advanced concepts for the design of civil engineering. The most important of them are reliability, robustness and durability. Robustness is not in the scope of this paper (it was achieved through several strategies, the basic of them being tying, alternative load paths analysis and consideration of key elements). Furthermore, special mention will be made to the flood protection of Qatar Rail assets, as per Qatar Rail Empl0yer's Requirements (ER) and Public Works Authority – Qatar Sewerage and Drainage Design Manual.

3.1 Reliability

In order to achieve the required reliability, all the necessary measures listed under Clause 2.2 (5) of EN 1990 have been taken (with further guidance from ISO2394, (Tanner et al., 2007; Tanner & Hingorani, 2010). The ones covered in this paper are:

a) The choice of partial factors for 120 years design life, and

b) Durability.

3.1.1 Determination of the target reliability index

According to a structure's Reliability Class, EN 1990 provides minimum values for the reliability index β for 1 year reference period as well as for 50 years reference period. It does not however provide any values for a reference period greater than 50 years, so the target minimum reliability index for the reference period of 120 years must be calculated. We know that:

$$P_f = \Phi(-\beta) \tag{1}$$

P_f is the probability of failure of a structure; Φ is the cumulative distribution function of the standardized normal distribution and β the reliability index. Equation (1) can be written for 1 year reference period:

$$P_{f,1} = \Phi(-\beta_1) \tag{2}$$

From the elementary probability theory we know that the probability of success P_s is:

$$P_s = 1 - P_f \tag{3}$$

Combining equations (2) and (3) we have:

$$P_{s,1} = 1 - P_{f,1} = 1 - \Phi(-\beta_1) = \Phi(\beta_1) \tag{4}$$

For *n* years of reference period:

$$\Phi(\beta_n) = [\Phi(\beta_1)]^n \Rightarrow P_{s,n} = \left[P_{s,1}\right]^n \tag{5}$$

Also, for *n* years of reference period equation (1) can be written as follows:

$$P_{f,n} = \Phi(-\beta_n) \Rightarrow \beta_n = -\Phi^{-1}\left(P_{f,n}\right) = \Phi^{-1}\left(1 - P_{f,n}\right) = \Phi^{-1}\left(P_{s,n}\right) \Rightarrow \beta_n = \Phi^{-1}\left(\left[P_{s,1}\right]^n\right) \tag{6}$$

The results of equation (6) are compared in the following Table 1 to the values of β provided in Annex B of EN 1990 for 50 years reference period and values are provided for 120 years.

Table 1: Comparison of minimum values for reliability index β (ultimate limit states) for 50 years and values for 120 years reference period

Reliability Class	Minimum values for β - *ULS*			
	1 year reference period	50 years reference period [EN 1990]	50 years reference period [equation (6)]	120 years reference period
RC3	5.2	4.3	4.42	4.22
RC2	4.7	3.8	3.83	3.60

3.1.2 Partial factors calibration

Based on the above reliability index, all the partial factors for actions and resistances have been calibrated. This has been done by multipliers that were the ratio of the design value of each variable for the reliability index for 120 years to the value for the reliability index for 50 years.

In the case of variable actions, especially the ones that are related to the climate and thus possibly affected by the climate change, their expected maximum values might increase during the design life. Assuming that the standard deviation remains the same over the considered design life, the increase of the mean value $\mu_{q,n}$ of the maxima of a variable load q for a reference period of 120 years is:

$$\frac{\mu_{q,120}}{\mu_{q,50}} = \frac{1 + \frac{\sqrt{6}}{\pi} \cdot V_q \cdot ln(120)}{1 + \frac{\sqrt{6}}{\pi} \cdot V_q \cdot ln(50)} \tag{7}$$

The same methodology was followed for the rest of the loads and resistances and it finally led to an increase of the partial factors for the variable loads (with the exception of traffic loads on railway bridges) from 1.50 to 1.60. All the remaining partial factors did not change compared to the ones for 50 years design life.

3.2 Durability

The Doha Metro is located in a very aggressive environment with high concentrations of chlorides and sulphates present in soil and groundwater, high air and groundwater temperatures, high humidity and wind borne salts. Special measures that ensure the durability have been taken for concrete structures and steel structures.

3.2.1 Concrete structures

The fib Bulletin 34 adopts two different strategies that can be followed, sole or combined, to ensure the durability of concrete structures:

- Strategy A: Avoid the deterioration due to the type and aggressiveness of the environment, e.g. by use of stainless steel, steel fibers, cathodic protection, etc.
- Strategy B: Select an optimal material composition and structural detailing to resist for the specified design service life the deterioration threatening the structure.

Bored Tunnels

For the TBM tunnels Strategy A has been followed by implementing Steel Fiber Reinforced Concrete (SFRC) for the segmental lining (see also ACI 5441.R). The possible deterioration mechanisms during their service life and their mitigations are shown in Table 2 below. Based on Table 2, it is believed that the bored tunnels will not be affected by the climate change.

Table 2: Deterioration mechanisms and mitigations for the Doha Metro bored tunnels

Deterioration mechanism	**Mitigation**
Chloride-induced steel corrosion	Chloride threshold of steel fibres 5 to 10 times higher than that of traditional reinforcement, depending on concrete composition and fibre geometry; fibres follow the setting of concrete, thus no voids; fibres are manufactured by cold drawing steel, thus reduced roughness and imperfections.
Carbonation-induced corrosion (internal surface only)	No/minimum carbonation in saturated/near saturated concrete; could happen at the internal surfaces (rust stains) due to availability of carbon dioxide. However, for water/cement ratios below 0.4, the thickness of such regions is not more than a few millimetres.
Stray current-induced corrosion (from the metro power traction)	As per the American Concrete Institute *"Since the fibres are short, discontinuous, and rarely touch each other,* ***there is no continuous conductive path for stray or induced currents*** *from electromotive potential between different areas of the concrete"*.
Sulphate attack	The CS 163 recommendations for the concrete composition and type of cement binder have been followed for the sulphate class S3.
Alkali aggregate reactions	Selection of non-reactive/inert aggregates.

Other Underground Structures (Stations, Troughs, Shafts, In-situ Tunnels, Foundations of Elevated Structures), Viaducts and Elevated Stations.

For these structures both Strategies A and B were combined (with more guidance based on (CS 163; Dauberschmidt, 2006; JCSS, 2001; QCS, 2010; Tang, 1996). The possible deterioration mechanisms during their service life and their mitigations are shown in Table 3 below:

Table 3: Deterioration mechanisms and mitigations for other underground structures, viaducts and elevated stations of the Doha Metro

Deterioration mechanism	**Mitigation**
Chloride-induced steel reinforcement corrosion	Strategy B: performance based durability modelling for carbon steel reinforced concrete to restrict the risk of corrosion to an acceptable limit.
Carbonation-induced corrosion (internal surface only)	Strategy A: Same as in bored tunnels..
Stray current-induced corrosion (from the metro power traction)	Strategy A: The provisions of relevant standards were followed (BS EN 50122-2, BS EN 50162 etc.)
Sulphate attack	Strategy A: Same as in bored tunnels..
Alkali aggregate reactions	Strategy A: Same as in bored tunnels..
Salt weathering	Strategy A: Properly consolidated and cured concrete with low water/binder ratio (< 0.40)

For the performance based durability modelling mentioned under Strategy B in Table 3 above, the *fib* Bulleting 34 model has been selected as service life design model. The key input parameters are quantified as probabilistic distributions.

As per *fib* Bulleting 34, the target reliability index towards reinforcement depassivation has been selected as 1.3 for the elevated structures and 0.5 for the underground ones has been considered as the waterproofing membranes are expected to provide a reliable protection for quite some years and they have been successfully used at similar projects in the region.

In order to verify the results of this probabilistic approach provided by the Design Consultants we have followed the approach in the second Strategic Highway Research Program (SHRP2) of the Federal Highway Administration of the U.S. Department of Transportation: we have carried out several Monte Carlo simulations with 10,000 (ten thousand) trials per simulation and the results matched the ones of the Design Consultants. This simulation was used to approximately predict the possible effects of the climate change. A conservative approach for the temperature was made, as we assumed that the average ambient and groundwater temperature is already 10ºC higher than the current average (32ºC). Then in our models we considered the most conservative chloride migration coefficients from the approved concrete mix designs. The results are presented in Table 4:

Table 4: Increase in temperature due to climate change - Monte Carlo simulation results for the reliability index for durability

Structure	**Target Reliability Index**	**Predicted Reliability Index**
Underground (except tunnels)	0.5	≈ 0.7
Elevated	1.3	≈ 1.0

These results show that for the underground structures there is no impact, while for the elevated structures the possibility that the reinforcement will start corroding after 120 years has increased from 10% to 15%. It is worth noting that the considered chloride concentrations in the groundwater are in the range of 22,000 to 25,000 mg/l which is higher than the salinity of the Mediterranean Sea. These higher values are data from only a few boreholes, whereas the majority of the boreholes tests provided values in the range of 2,000 to 5,000 mg/l. It is reasonably believed that any future groundwater contamination due to the climate change is covered by the chloride concentrations considered in the models.

3.2.2 Structural steel structures

The steel structures of the Doha Metro are located in a C2, C3 or C5-M environment (ISO 12944-2) and are protected with duplex coating. Based on the design, the minimum expected service life of the duplex coating system is 440 years for the C2 environment, 135 years for the C3 environment and 53 years for the C5-M environment.

The coating of the steel structures in C5 environment might start deteriorating at around 53 years, even earlier if the average air humidity and the number of humid days increase due to climate change. Although the situation is better with steel structures in C3 environment (current expectance of coating deterioration is at 135 years), climate change might reduce the expected service life of the coating. Therefore, regular inspections are expected.

The elastomeric bearings comprise stainless steel for the sliding surfaces and carbon steel parts that are classified under C5-M environment.

3.3 Flood protection of Qatar Rail assets

While flooding is not directly connected with the structural issues discussed above, it is a major threat to any metro. The Doha Metro is not an exception. Doha has undergone a very rapid development during the past years. As a result, many open areas, where previously permeable surfaces existed, have been paved, substantially affecting the storm water runoffs situation. Consequently the past flood records would have proved insufficient to assess the risk of flooding of Metro underground structures.

In addition to providing a design that meets Qatar Rail Employer's Requirements (ER) the Contractors were requested to perform assessments of the flooding risks at multiple locations for all the structures and establish design flood levels derived from external and internal flood sources (see Qatar Rail flood risk assessment reports).

Storm scenarios were studied assuming functional effective storm water drainage (Scenario 1) and, non-functional storm water drainage (Scenario 2). In addition, the consequences of utility bursts were also reviewed along with hazards posed due to rise in seawater and ground water levels. The critical flood levels at each asset were defined as the worst case predicted flood level of all of these sources for both Scenarios (1) and (2).

Considering the design life time of Doha Metro of 120 years, in order to account for predicted climate changes over the next century, the flooding models have taken into account the results of Ministry of Municipality and Urban Planning (MMUP) study on regional design rainfall in Qatar and of United Nation's Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5), by applying a defined climate factor.

A holistic approach was required for the modelling, as various flood elements could interact and/or occur simultaneously. Combined events were investigated, such as:

- Interaction: surface drainage system and coastal flooding,
- Interaction: surface drainage system and groundwater,
- Combination event: utility burst and rainfall event, and

- Internal flooding: caused by water tank leakage/overflow, water pipe leakage, sprinkler/fire water discharge and drainage system malfunction.

Simulations of surface water hydraulic behavior for a selection of storm profiles representing different storm duration and return period, as defined by the Qatar Rail ER, were carried out. The hydraulic models covered areas of interest in adequate detail to investigate the potential flooding at each asset site in both Scenarios (1) and (2). No modifications or options have been applied to the base model provided. The hydraulic models created allowed any predicted flooding from the surface water network to be mapped as it flows overland, modelled and quantified any ponding in the vicinity of the assets and defined the worst case flood elevation as the Design Flood Level. In alignment with industry best practice, a minimum asset level (freeboard) above the Design Flood Level has been defined in Qatar Rail ER in order to take account of:

a) Contingency for uncertainties in modelling data, and
b) Dynamic effects such as wind-blown effects and minor wave effects.

The urban development of the city of Doha is a very fluid environment and the coordination with interested Stakeholders required a constant re-iteration and update of the flooding models and entrance levels. This was feasible up to a point in time where the construction of the Metro assets progressed to an extent where the changes of the structures were not feasible anymore. Later developments of the city infrastructure may have altered, at particular locations, the flood prediction and, consequently, the established Design Water Level at the same locations. Nevertheless, in order to ensure the protection against the flooding risk, Qatar Rail performed simulations of the impact of changes on the entire Metro network combined with jointly inspection with interested Stakeholders. As a result, assets potentially exposed to a defined gradual flood risk, as consequences of changes, were identified and construction measures by Qatar Rail and/or interested Stakeholders combined with operational measures were defined and implemented.

It is worth mentioning that the city of Doha is still under development, especially near the Metro assets, and future changes would require revisiting today's configuration, followed by construction and operational measures to ensure a continuous flood protection of the Metro assets.

4 CONCLUSION

The major structural/civil design provisions against the effects of climate change for the Doha Metro have been presented in this paper. The combination of considered reliability requirements, durability modelling and conservative values for the loads (climatic or not) dictated by Employer's Requirements (e.g. groundwater level at ground level for the permanent structures) safeguards the resilience of the Doha Metro against the climate change from a structural point of view.

However, it should be noticed that all the work presented in this paper has been carried out based on tools and data that we have in our hands today. Sophisticated climate models and tools are being constantly developed and will continue to do so. Weather data should be collected, analyzed, evaluated and compared to the assumptions regarding climate in this paper. Additionally, regular inspections and structural monitoring would be of utmost importance for such an important project.

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