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Deteriorated Concrete Foundation on the Gulf Coast

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SYNOPSIS: An investigation into the deteriorated condition of a concrete mat foundation under saline water table on a coastal sabkha sand in Qatar, the Arabian Gulf coast, was undertaken. The investigation aided by visual examination, testing (destructive and non-destructive), analysis and consideration of different soil-structure interaction schemes resulted in re-approval of the foundation from a structural integrity point of view; however its water tightness role was judged inadequate and required remedial works. Options for repair of the foundation were examined and proposed. To safeguard against the adverse effects of salts on foundation concrete, appropriate design and construction measures are required.

INTRODUCTION

The coastal plains along the southern shores of the Arabian Gulf are often backed by broad intertidal flats and fringed by shallow seas of very high salinity. Their shallow groundwater is generally extremely rich in sulphates and chlorides, and the shoreline sediments are commonly loose to moderately dense silty sands, shelly sands, carbonate silts and clays. The sediments are variable and may also include aeolian deposits and fluvial gravels. In the hinterland, some distance away from the coast, the same kind of sedimentary and groundwater conditions can occur (Akili & Torrance, 1981; Fookes et al, 1985). Fig. 1 shows the major salt flats (sabkhas) along the southern coast of the Gulf.

These coastal zones have been frequently chosen as sites of major civil engineering works where their sediments and waters come in direct contact with concrete and structural steel. Usually, problems arise due to the chemistry of the sediments and their groundwater and it is the geochemistry of these environments that is not taken into consideration, leading often to undesirable consequences.

The relatively high air temperature, the low seasonal humidity and the gusty winds tend to promote evaporation from the surface and hence cause continuous transport of groundwater through the capillary fringes for up to several metres above water table. These factors tend to speed up precipitation of minerals at the water table, within the capillary zone or within a particular layer of soil or even at the rock surface below. The flow also brings about the solution of soluble minerals within older sediments beneath the water table (Akili & Torrance, 1981; Fookes et al, 1985).

The rate of solution or precipitation of minerals varies with:

(i) the flow rate through the sediments,
(ii) rapidity of water evaporation via the capillary fringes,
(iii) individual properties of the rock - soil - water systems and
(iv) the nature of the engineering works themselves (excavation, dewatering, filling, concreting, piling, etc.).

The most common minerals that can precipitate and dissolve at significant rates include: gypsum, anhydrite, calcite and halite. Although much of the solution/precipitation processes tend to occur between the ground surface and the ground water table; observations show that these processes may extend downward into deeper stratas to encompass a zone of two to three metres below the base level of the structure itself.

This paper presents the findings of a diagnostic investigation of a deteriorated concrete foundation, designed and built in 1980, in an industrial site along the coast of the State of Qatar, The Arabian Gulf.

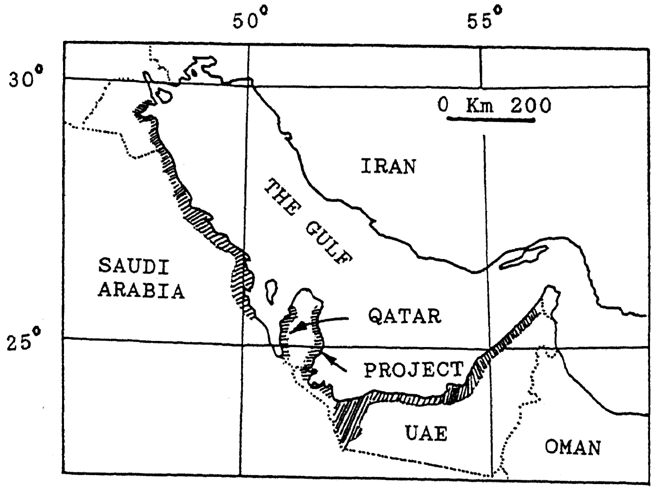

Fig. 1. Location of major sabkhas along the southern coast of The Gulf

Due to geochemical imbalance in the foundation environment and lack of concrete protection underneath the foundation, the structure (mat) has suffered rapid deterioration which has resulted in cracking and spalling of concrete in addition to rusting of the reinforcement. As a consequence leakage of groundwater into the building has hampered its water tightness role and prompted action to be taken to evaluate the situation and to propose remedial works.

The increasing trend towards rehabilitation rather than replacement of deteriorated concrete structures, has resulted in an increased burden on the consulting engineer to attempt to understand the causal factors, to assess the deteriorated condition of the structure and to predict its safe remaining life.

LOCATION & SUBSURFACE

The project site is located 30km south of Doha, the capital of Qatar. The site is about 500m from the coastline. The landward sides of the area can be described as low lying sabkha dotted with sand dunes. The building under consideration here is bordered to the south by a gently sloping large size barchan dune that rises to a height of 25 metres. The dunes in the area are under the influence of a north westerly "shamal" winds that blow sands into the site, in a seaward direction for about one hundred days a year. The dunes are rapidly migrating to the sea, prograding the coast to produce a predominantly sand sabkha, characterized in profile by an extensive sandy layer that overlies a weathered rock with relatively shallow ground water table laterally connected with sea water.

The dominant rock strata underlying the sabkha is the Simsima limestone formation, a fossiliferous fine to medium grained whitish to brownish chalky limestone. The limestone is highly weathered at its top, poorly bedded, rarely crystalline and contains: small voids, irregular joints and fractures that are often filled with sands, silts and clays. It is variably indurated and highly dolomitized within the upper five metres.

The ground condition at the site may be divided into five lithological categories. The uppermost layer is Made Ground to a depth of 3.0m. Below the Made Ground, naturally deposited sabkha sand prevails down to a maximum thickness of 17m. Within this layer there is a distinct colour change from brown to dark grey at a depth varying from 8.5m to 11.0m. This change in colour probably represents a change in deposition or possibly a change in the source of the material deposited. Occasional shell fragments are found within this layer. Standard Penetration Tests within the sand layer show a marked decrease in N value at 4.0m, from around 33 to around 10, thereafter - below 4.0m - gradually increasing with depth. A layer of hard grey/green laminated clayey silt, around 2.5m thick, underlies the sabkha sand. Below the clayey silt, a dense to very dense silty sand with shells occurs down to bedrock. Bedrock comprises a thin layer of heavily weathered and decomposed limestone, which grades into moderately weathered dolomitic limestone with gypsum.

The Made Ground is a compacted desert fill of a selected size range placed in layers and derived from near surface comprising sand and some angular to sub-angular limestone gravel and rock fragments.

DESIGN AND CONSTRUCTION INFORMATION

The building is a rectangular single storey structure with a flat roof and a deep basement under the entire building plan. The plan dimensions are 28.2m by 17.9m and the building above and below ground is designed as reinforced concrete box. See Figs. 2 and 3 for relevant details. Above ground level, the building is enhanced by cladding with coloured profiled steel sheeting. The basement is 3m deep and divided into several rooms housing airconditioning plant, electrical equipment and some delicate instruments.

Excavations along the side of the building revealed that the foundation was resting on natural soil (sabkha sand) rather than Man Made ground. Tidal records made available indicate a difference of two metres between high and low tides in the proximity of the building. Measurements taken from ground surface to water table levels indicated that changes in ground water levels near the building tend to follow tidal fluctuations and appear to be almost of the same order of magnitude.

Available design information of the building has revealed that the basement was designed as a 250mm thick reinforced concrete mat thickened at the edges and in the centre to 600mm. The mat is assumed not to be supported directly on soil. The total weight of the building is assumed to be supported on the thickened part of the mat (600mm) underneath the two exterior walls and underneath the interior wall of the building. See Fig. 2 and 3 for details. An examination of the reinforcement details whereby heavy reinforcement is placed at the bottom of the slab (at midspan) and at the top of the mat (at the wall supports), confirms that the mat was intended to span between wall supports. This arrangement of reinforcement ensures that the loading on the mat will cause vertical deflection downwards at mid span. Whether the assumed design concept - upon which reinforcement was selected and placed - is appropriate required some checking by considering various loading scenarios.

Within a few years of its construction, the basement floor, being under the ground water table, showed signs of leaking water. The ingress of ground water into the structure has been of concern due to the delicate nature of the equipment the basement contains.

THE INVESTIGATION

In late 1990, the writers were called upon to examine the deteriorated concrete condition of the mat, evaluate suggested remedial measures proposed by consultants and advise on how could the basement be put right. The tasks undertaken have included:

(i) survey and inspection of the current condition of the building and its basement slab and walls;
(ii) review of design documents, as-built plans, soils and foundation information, and suggested remedial schemes proposed by consultants;
(iii) structural and stress analysis of the building to verify compliance with design norms, assess the adequacy of the structure as a whole, identify critical locations in mat and, appraise the structural integrity of the mat.

Whether the mat bottom steel and exterior wall reinforcement has corroded was a key question upon which the details of an appropriate remedial scheme hinges.

The problem, in general, was viewed from two angles: (a) the water ingress to a sensitive area housing delicate equipment and, (b) the extent of the structural degradation of the basement and whether the safety of the building as a whole is in jeopardy?

The visual examination conducted has confirmed that the basement slab suffers from cracking, spalling, rusty reinforcement and water ingress.

Observations of concrete surfaces was augmented by the following means:

(i) metallurgical examination of corroded upper reinforcement and determination of tensile strength of selected reinforcing (corroded and uncorroded) bars;
(ii) measurement of concrete cover and spacing of reinforcing bars;
(iii) taking cores and other samples of base slab and walls for testing and analysis;
(iv) testing for depth of carbonation by means of a chemical indicator applied to freshly cut concrete surfaces;
(v) excavation and exposure of external wall surfaces to foundation level;
(vi) application of the Schmidt hammer at predetermined locations as a means of detecting, by a non-destructive procedure, the relatively low strength concrete areas on the upper surface of the mat.

Concrete samples taken from basement surface were examined, photographed and tested to provide information on: (i) presence of voids, honeycombing or cracks and quality and type of aggregates used; (ii) cement content and cement type; (iii) chloride content; (iv) sulphate content; (v) depth of carbonation; (vi) bulk density and (vii) estimated compressive strength (on cores only).

Samples of reinforcing steel were also obtained from locations where spalled concrete was removed. Each sample was measured to determine its effective cross-sectional area and later tested to determine its tensile strength.

Observations of the outer concrete of the mat and buried walls, facilitated by means of two excavations made down to below base level, did reveal one vertical crack about 100 mm from one of the corners. The crack was 1m long, 3mm wide and 50mm deep at its worst point. The side of the mat was protected with a thick bitumen coat which continued horizontally and was brought up the wall to terminate about 220mm above the top of the base. No protection however was provided at the bottom of the mat.

Table I shows results of tested samples from mat surface and basement wall. Fig. 2 shows inspected areas, test locations on mat and defect type noted. Thirty two locations were closely examined (Fig. 2) and were subjected to testing by the Schmidt hammer device. The Schmidt hammer is a spring-loaded impacting device that incorporates a scale to measure the energy of the rebound folowing the impact. The test gives a quick means of estimating the concrete strength.

In more specific terms, detected deterioration can be summarized as follows:

(i) spalled concrete cover (SC) was noticed at six different locations as shown in Fig. 2. Measured concrete strength at these locations was relatively low indicative of hollowness, delaminations and rusty upper reinforcement.
(ii) Badly rusty upper reinforcement was noticeable at three locations with signs of water leaking into the basement from these

TABLE I. Mechanical and Chemical Test Results on Samples from Top of Mat and Basement Wall

Location	Sample No.	Density Kg/m^3	Strength N/mm^2	Cement Content, %	Chloride Content, %	Sulphate Content, %	Steel Condition
Top of Mat	1	2331	29	-	0.21	0.57	
	2	2361	40.3	-	0.45	0.70	very rusty
	3	2366	35.8	-	0.26	0.57	very rusty
	4	2382	-	21.6	0.73T/0.27B	0.61/0.39	very rusty
	5	2339	-	21.2	0.32T/0.87B	0.54/0.58	very rusty
	6	2307	-	22.6	0.78T/0.82B	0.61/0.56	no steel
Basement Wall	1	2408	53.4	-	0.13	0.47	good
	2	4397	42.2	-	0.08	0.43	good
	3	2369	41.8	-	0.16	0.51	good
	4	2344	38.6	-	0.08	0.46	good
	5	2355	34.6	-	0.16	0.49	good
	6	2361	37.9	-	0.13	0.50	good

locations.

(iii) previously repaired areas (Fig. 2) have not properly withstood the onslaught of the aggressive environment and appeared to have failed; indicative of an inferior repair technique.

(iv) The relative variation in the Schmidt hammer readings from one location to another - not shown here - appeared consistent and reflected the relative condition of the upper concrete surface of the mat, i.e. relatively low values exhibited did correspond with damaged area identified visually and by sounding. Additionally, the Schmidt hammer readings agreed well with compressive strength data of tested cores reported on in Table I.

(v) A certain amount of convexity was noticeable at several places and is believed to be caused by corrosion of reinforcement rather than camber in the structure itself.

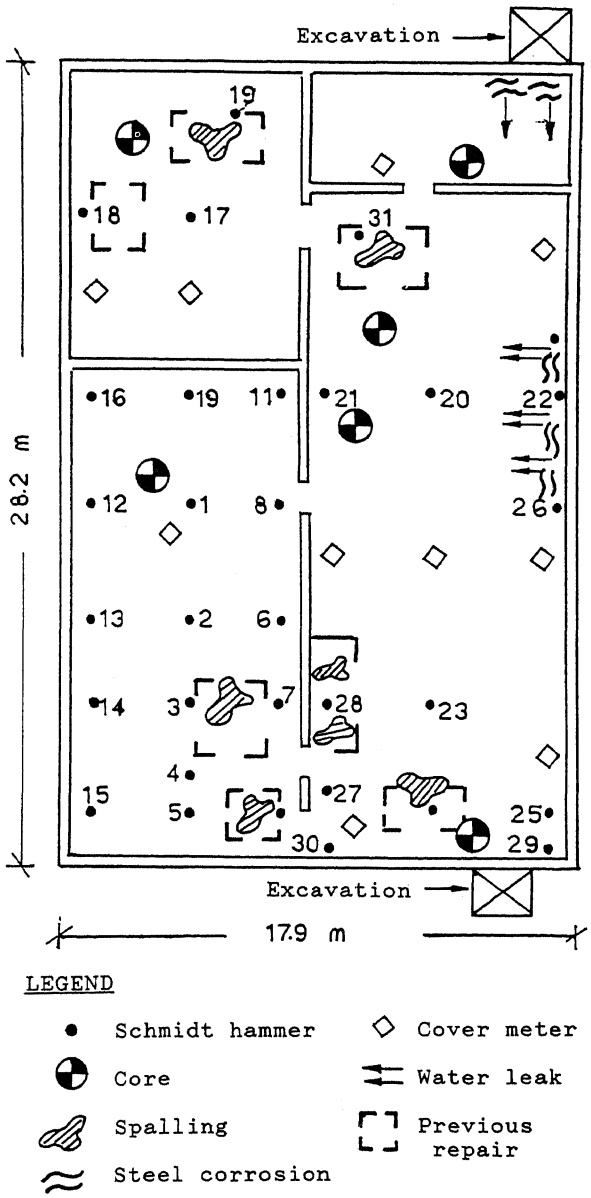

Fig. 2. Basement plan showing deteriorated areas and test locations

Overall, it appears that the damage (from the top) is widespread and covers an estimated surface area of about 30% of the overall mat area.

STRUCTURAL ANALYSIS

Structural analysis of the mat was performed using a computer program that takes into consideration the soil structure interaction, water uplift and imposed loading. The aim of the program is to search and identify critical locations and in particular potential areas of cracks in the mat. The building was analyzed as one structural unit - as typically shown in Figure 3 - where the building was divided into 24 members connected to 21 nodes. Based on available soil information a value of 10,000 KN/M^3 was assumed for the subgrade reaction modulus. Acting loads assumed were those reported by the designer. Dimensions were assumed as those given in the as-built drawings. A strip of unit length of the building was analyzed.

Three different cases of mat loadings were considered. The <u>first</u> case assumed the mat to be resting directly on the soil with uplift ground water pressure acting. The <u>second</u> case assumed the mat to be supported on wall footings only with uplift pressure acting. The <u>third</u> case assumed the mat to be supported on wall footings (similar to second case) with no uplift pressure. It should be noted that the third case was that assumed in the original design. The analysis has enabled us to map out from the deflected shapes of the mat the distribution of bending moments and the soil pressures acting at the bottom of the mat. Table II provides a summary of the calculated moments at selected sections of the mat - a total of six sections were considered. The moments considered were: M_{CR} = moment required to induce cracking, Mu = ultimate resisting moment and Ma = applied moment. M_{CR} values were obtained assuming an allowable tensile strength of concrete of 3 Mpa. This value is equivalent to one tenth the average compressive strength derived from the Schmidt hammer readings.

Comparison between applied bending moment and required moment for cracking (M_{CR}) leads to the following:

(i) should the <u>first</u> case of loading prevail (acting soil pressure + water uplift) then longitudinal stress induced cracking is eminent at several sections. As a consequence, longitudinal cracks could have occurred at the top and bottom of the mat.

(ii) should the <u>second</u> case of loadings prevail (soil pressure under wall footings only + water uplift), no stress-induced cracking would be expected.

(iii) the <u>third</u> case of loading (soil pressure under wall footings only with no water uplift pressure) corresponds with the assumption made in the original design; leads to stress-induced cracking at several sections. However neglecting water uplift is not realistic unless groundwater is drawn down permanently - which is not the case here.

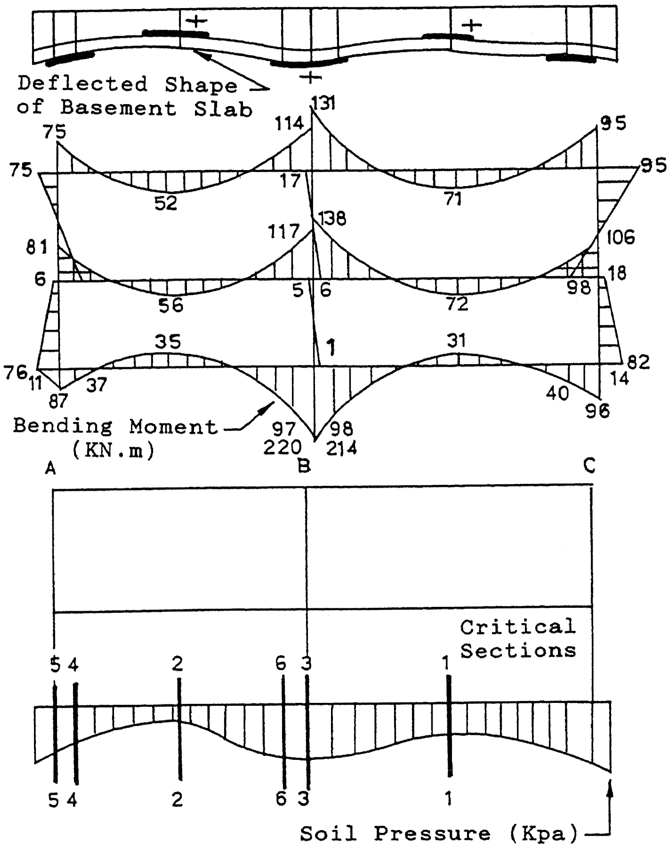

Fig. 3. The deflected shape of basement slab, bending moment diagram and soil pressure (Case 1)

Based on the outcome of the analysis, stress-induced longitudinal cracks could have developed at the bottom of the slab shortly after construction and commissioning. These cracks could have widened with time allowing salt water to seep upward through the concrete; particularly so since no water proofing was applied at the base of the mat.

MAT CONDITION

The condition of the mat, based on writers survey, analysis and findings, can be summarized as follows:

(i) The floor slab suffers primarily from rusting of the reinforcement caused be ingress of salt water into the concrete slab. The rust is growing progressively at a relatively slow rate. Rate of rust is a function of moisture content and availability of oxygen at different parts of the slab.

(ii) Although the extent of damage cannot be accurately determined, it is believed to be more widespread at the top surface due to available oxygen needed to sustain the reaction. Corrosion is an electrolytic process which needs moisture in the concrete to provide conductive electrolyte and oxygen at the non-corroding points (cathodes) to sustain the reaction which provides current for the corroding points (anodes). (CIRIA, 1984; Pullar-Strecker, 1987)

(iii) Under the prevailing uplift pressure - estimated at an average of 15 kpa - the salt water has ingressed and moved up through pores in the slab and/or through stress-induced cracks believed to have developed early on. It is rather unfortunate that the durability aspects of the mat structure were totally neglected. The minimum that could have been done is to provide an impermeable membrane at the bottom of the mat.

(iv) The primary cause of the damage - as often is the case in many areas along the Gulf - is attributed to high chloride content that has contaminated the concrete and found its way to the boundary between steel and concrete.

(v) Despite the deteriorated condition of the mat, it was judged to be safe against any sudden failure or collapse. Its water tightness role has however been hampered. In order to restore its water tightness role, certain measures should be taken.

TABLE II. Comparison between Applied Moment (M_a) and Resisting Moments ($M_{c\ell}$, Mu) at Different Sections

Section Location	Slab thickness (mm)	Applied Moment (KN.m) M_a Case 1	Case 2	Case 3	Resisting Moments (KN.m) $M_{c\ell}$	M_u	Expected Crack Locations
*							
Sec. 1-1	250	31.0T	3.0B	33.0B	34.3	43T/46B	None
Sec. 2-2	250	35.0T	15.5B	37.0B	34.0	26.6T/53B	Top Surface
Sec. 3-3	600	219.5B	68.0B	6.0T	198T/135B	188T	Bottom Surface
Sec. 4-4	250	40.0B	32.0T	59.0T	34.6T/53B	26.6T	Bottom Surface
Sec. 5-5	600	87.0B	21.0T	62.0T	196.0	188/96.5B	None
Sec. 6-6	250	97.0B	4.0T	53.0T	35.0	26.6T	Bottom Surface

Case 1: Mat on soil + uplift; Case 2: Mat on thickened wall footings + uplift;
Case 3: Mat on thickened wall footings + uplift
* See Fig. 3 for section location
T Top surface
B Bottom surface

RECOMMENDATIONS

The outcome of the investigation has clearly shown that serious deterioration has taken place. The concrete in the mat suffers from a significant level of chloride and rusty reinforcement.

Accepting the fact that the mat structure can not be restored to its original sound condition; several options may initially be cited. These are:

(i) do nothing save running periodic checks and thus allow deterioration to run its course;
(ii) take action by preventing the deterioration from getting worse;
(iii) carry out repairs to restore deteriorated parts to a satisfactory condition;
(iv) demolish and rebuild the mat.

After consultation with the owner it was decided to go for a relatively high-cost fundamental repair that reaches down to all contaminated areas rather than a low-cost patch repair which had been tried with not much success in arresting deterioration. Bearing this in mind we recommended the following steps to be carried out from within the building:

1. To map out the whole slab and walls to locate all deteriorated areas including: delaminations, voids, weak concrete, cracks and rusty reinforcement.
2. To break out spalled concrete cover down to a depth below reinforcing bars. This is to be done vibration free.
3. To remove all contaminated concrete using methods and equipment that would maintain dust free environment in order not to adversely affect delicate equipment housed within the building.
4. To clean reinforcement and coat it with an appropriate rust inhibitor.
5. To replace all corroded reinforcement and restore it to its original cross-sectional area.
6. To inject and seal any visible cracks using suitable material.
7. To replace deteriorated concrete with an impermeable concrete mix to be prepared with relatively small maximum aggregate size and with shrinkage compensation admixture.
8. To apply a compatible finishing coat that will bond well to repaired and unrepaired concrete surface that possesses protective properties and provide a proper finish.

If repair work is properly executed, it should curtail further deterioration, prevent leakage and extend the serviceable life of the mat for a considerable period (say 8 to 10 years). Apart from this repair, a commitment to periodic monitoring and occasional light type repair - such as recoating - should be regarded as an integral part of the repair strategy that should not be neglected.

The added protection that may result from attempting to seal the external surface of the slab and wall may not produce the required results. This is simply because complete encapsulation from outside is a must in order for the protective layer to be effective. Since such complete encapsulation can not be verified, the added cost- relatively large repair cost - involved may not be fully justifiable. Additionally, since applying a sealant on the outside surface (mortar, epoxy - resin, microsilicates,...) requires drilling a relatively large number of holes into the slab to inject sealant; the effect of the drilling process on the continuity and strength of the slab should not be minimized as drilling (a dynamic process) may propagate and extend existing cracks in the slab. The writers are of the opinion that this type of repair (sealing the external surface) is rather difficult to apply effectively and should be thoroughly investigated before resorting to it.

SUMMARY AND CONCLUSIONS

An investigation into the deteriorated condition of a concrete foundation for an industrial building on a sabkha sand erected in 1980 on the coast of Qatar, the Arabian Gulf was launched to examine the causes of deterioration, assess the remaining life of the concrete mat and recommend a suitable repair strategy. The investigation was aided by testing, analysis and consideration of different soil-structure interaction scenarios. The outcome has shown that the concrete mat suffers from cracking, spalling and corroded reinforcement to the extent that it has impaired its water tightness role - being under saline ground water table - but judged to be safe - structurally - against sudden failure.

Inadequate design and absence of foundation tanking resulted in sea water perculation into the mat and chloride induced depassification of the slab top reinforcing bars. A repair scheme supplemented with continuous monitoring would extend the useful life of the structure for an estimated period of eight to ten years.

To combat foundation deterioration, routine design and construction procedures need to be properly modified to safeguard against adverse chemical reactions between materials of construction (steel and concrete) and the geochemical hazards of the Gulf environment.

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