A Critical Evaluation of Salt Weathering Impacts on Building Materials at Jazirat al Hamra, UAE.

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Abstract

Salt weathering results in the breakdown of surface materials and is common in dryland areas. This paper investigates the degree of damage to buildings in Jazirat al Hamra, UAE, which is located on the coast and lies between two sabkhas. The town is one of many sites along the Ras al-Khaimah coastline that have current construction projects with the prospect of further developments. It would be highly beneficial for the construction industry to have a better understanding of how detrimental salt weathering mechanisms such as crystallisation and salt efflorscence can be to modern building materials such as concrete. Salinity values from sediments and observations of damage to structures (of different ages) were recorded along four transects. The transects were oriented to cover the town in all directions to take into account the effects of aspect. This data enabled salinity ranges and building age to be mapped in zones. This enabled analyses of location, climate, aspect and wind influences on salinity levels and building ages according to construction materials. There was a strong correlation between damage, salinity levels and location as well as the beach and sabkha areas being strongly affected. The location of the different ages of buildings were established due to the gradual growth of the town, and the salinity values were affected by the materials used. Modern porous building materials such as Portland cement contained a high content of sodium chloride. The older materials (e.g. bioclastic limestone) have low porosity and better cohesion compared to bricks and cement and this was indicated by the differences in damage levels observed between the ages. The prevailing winds (NNW) appeared to have a greater influence on the results than did aspect. Some damage to structures is shown to be unavoidable and therefore effective preventive practices should be included in all development designs in this location.

Keywords: sodium chloride, sabkha, Portland cement, calcarenites, crystallisation, capillary action

Introduction

The town of Jazirat al Hamra sometimes known as the 'Red Island', is located on the northern coastal part of Ras al-Khaimah, United Arab Emirates (UAE), the red tower (N 25˚ 42.539'E 55˚ 47.831') is in the town-centre.

Jazirat al Hamra, as part of the coastal zone has been under development for hotels, housing complexes, power stations, water treatment plants and fishery areas since the 1960s (Goudie et al, 2000). This is due to the success of Dubai's development which has boosted UAE's economy through employment and tourism and increased investment. However, there is a lack of knowledge of the coast's history and dynamics which have already started to modify the coastline.

Jazirat al Hamra was originally an island (it is now linked to the mainland by reclaimed land) and an ancient settlement overlying ancient sabkha and oyster reef sediments (Goudie et al, 2000). The shell middens and the mangrove species date the sabkha back to the Mid-Holocene (Vogt 1994). Archeological evidence (flakes, blades and tools made in the Qatar D industry and Late Neolithic period) indicates two main periods of occupation (Beech and Kaliweit, 2001) when occupants kept domestic livestock. Marine resources (such as crab and dugong) were also exploited.

This former island and bar, spit and lagoon complex was changed by the infilling of the north end of the two southern sabkhas and the dredging of a harbour (Goudie et al, 2000). This disruption may have caused sea water intrusion into the coastal aquifer as has occurred in Bahrain (Doornkamp et al, 1980). Exposure of the shoreline, notwithstanding groyne construction, is causing landward migration (Goudie et al, 2000). Dredging and reclamation continue to modify the coastline and have stimulated sediment flows and spit thinning and detachment are perhaps leading to instability (Goudie et al, 2000).

The purpose of this paper is to determine, by examining buildings and their aspect, whether salt-induced weathering is occurring. A classification of weathering to buildings can determine the extent of damage (perhaps due to the influence of aspect) and that should be of use to developers in such a coastal environment.

Background

Salt weathering

Salt weathering involves natural salts (disruptive chemicals) which physically disintegrate rock and building materials. Sodium sulphates and nitrates, and calcium carbonates and sulphates are more destructive than sodium chloride (Chapman 1980; Cooke et al, 1993). Sodium chloride's role has to be considered as the town has a coastal location and the salt builds up either at or near the rock surface. Salt would come from sabkha deposits in the coastal inlets where the wave energy is low enough for settlement of silt and clay (Juillie and Sherwood, 1983). The deposits are loose or soft material that contains significant amounts of organic matter and are the outcome of natural erosion (Erol 1989). Jazirat al Hamra lies in the north of a large plain (which has sabkha deposits) between the Oman Mountains and the Arabian Gulf, with the great sand dunes of Arabiaat to the south (Goudie et al, 2000). The town is in a hot arid environment with ~120 mm or less annual precipation (Goudie et al, 2000). It therefore has a low relative humidity and high daytime temperatures/evaporation rates (with extreme ranges) in excess of annual precipitation. Akili and Torrance (1981) say these conditions would lead to accumulation of evaporites at shallow depths causing both salt encrusted sabkha sediments and ensuing engineering problems arising out of its variable nature, poor mechanical properties and high organic content (Erol 1989). This is becoming a widespread problem with extensive construction across the Middle East particularly in the coastal belts where sabkha deposits are found (Khan and Hasnain, 1981).

The groundwater conditions are an important control on the degree of salt weathering causing surface and near-surface evaporation, saline concentration and capillary migration. Both Cooke et al, (1993) and Doornkamp et al, (1980) explain the principle of the capillary fringe height, determined by the water table depth. The potential height of capillary water may rise from the groundwater bodies above the ground surface. The height will vary due to the nature of materials above the water table; in particular sandy soils between 1 m and 1.5 m (Doornkamp et al, 1980). When the capillary water extends to the surface, the surface materials become moist and suffer from extensive evaporation with puffy ground crusting and salt effloresence (Doornkamp et al, 1980; Pel et al, 2004).

Crystallization is the process whereby crystal growth occurs within a rock (often near its surface), it follows the movement of saline solutions through the material by capillary action. Changes in the concentration of solutions (by evaporation), or changes in temperatures of solutions prompt this process (Goudie 1994). The higher the salinity the greater the potential for crystalization and therefore for potential pressure exertion on the rock materials (Winkler and Singer, 1972). This, and results from Rijniers et al (2005) using nuclear magnetic resonance, indicate that pressure within crystals develops; the crystal takes the size and radius of a pore within a material thus causing its own surface tension to be transferred to the pore wall. This strongly suggests that pore size is another factor that determines stress development and the distribution of pores (porosity) that will establish the resistance of the rock material (Ruedrich et al, 2007).

Building Materials

Salt-induced deterioration of inorganic porous building materials such as concrete in this region can be traced to the effects of geological and climate characteristics of the area (Cady 1986). The deterioration intensity depends on salt types, its content in buildings (and distribution), the porosity of materials and moisture absorption and circulation between dissimilar porous media, relative humidity and temperature (Cultrone 2007; Lubelli et al, 2004). Other properties such as water absorption capacity, potential crack formation, tensile strength and bedding-plane orientation will determine how a material will respond to salt weathering (Cooke et al, 1993; Chapman 1980).

Bricks, calcarenite and mortar which are porous are some of the most common building materials worldwide. Bricks are silicate-based, calcarnites are calcareous (shell based limestone) and mortars are commonly made of silicates and carbonates (Cultrone 2007). Solutions move through these materials at differing speeds which leads to a build-up of fluids and hence salts in some areas, which can increase the intensity of damage. Cultrone (2007) carried out freeze-thaw tests which show that joints between calcarenite and mortar are stronger than those between brick and mortar due to differences in the structure of the contact area and the composition.

Lubelli et al, (2004) measured brick moisture content by comparing different brick core depth weights. The results showed that the lower zone had more moisture and this decreased as the height (and zone) increased. The moisture also was less inside compared to the outside, something in common where moisture distribution arises from capillary action. More sulphates were found at the bottom, being less soluble salts than nitrates and chlorides, and so cannot be transported to higher levels. However, Lubelli et al (2004) did find that the upper zone of the wall had high moisture content and sodium chloride as a powder, due to a different mechanism (sea spray) bringing salt in contact with moisture.

Evaporation takes place when relative humidity exceeds the water vapour in the saline solution in two phases (Benavente et al, 2003). The first phase is surface evaporation depending on capillary forces and composition of the solution; the second phase is the slower evaporation rate in the drying process (where the majority of salt crystal growth occurs) corresponding to diffusion of water vapour inside the pores. Benavente et al (2003) came to the conclusion that pore size affected the evaporation phases as it favoured larger pores, thus helping to create saturated solutions for crystallization to occur in highly soluble salts.

Aspect

The sun's direct and indirect radiation can influence water evaporation rates and therefore capillary action through the creation of high surface temperatures. The sun's position in the sky and orientation of the surface controls the direct solar radiation (Castenmiller 2004); east-facing vertical surfaces will receive direct radiation from sunrise and west-facing ones after midday. Hence the east- and the west-facing vertical surfaces will receive more radiation than a south facing vertical surface, as they have complex thermal and humidity regimes that enhance weathering (Smith 1978 and Paradise 2002). These regimes are explained by Castenmiller (2004).

Method

Using a Global Positioning System (GPS) receiver (Garmin eTrex Summit) and a compass, four transects (T) were formed covering most of the town (see figure 1). Every 25 m (approximated owing to intervening obstacles) a sample of sediment (for salinity) and photographs were taken (where possible near a building). GPS readings were recorded and a written account made of any observations of the general location, vegetation cover, aspect of building and its age according to the construction materials (see table 1).

Age Category	**Building Material**
Old (100 years +)	Coral/shell (bioclastic limestone) breeze blocks and mortar
Intermediate (50-100 years)	Breeze blocks (some shell) with render and mortar (some pebble dash)

Modern (0-50 years)	Breeze blocks with render and mortar, cemented pebbles, concrete foundations, pebble dash, painted and some with steel reinforcing rods for structural support

Table 1: Age of Buildings

The classification of weathering on some buildings (and heights of capillary action) were examined for the level of salt weathering damage to see if there was a link between weathering and aspect and/or location (see Table 2). The dredging and infilling of the sabkhas was considered when analysing the salinity readings along each transect. The salinity levels for each sample of a transect were plotted on a graph to ascertain if there were any trends linking them with locations in the town. The salinity levels and building ages were zoned on scaled town maps. The higher the salinity the more the expected damage undergone to the building; subject to time and type of building materials used. This ascertains whether location can determine salinity levels or the vulnerability of the building materials used.

	Classification of Weathering
1	Recent building - no cracking or only a little affecting the surface materials above the ground only (e.g. to the paint) (measured in metres)
2	Cracks to the outer layer, may be a layer off showing rendering Discolouration (from hydroscopic processes) high up the wall
3	Breeze blocks showing - more cracking and the cracks are wider and extend higher
4	Extensive cracking, block work exposed and beginning to weather, weathered holes in the render
5	Rubble

Table 2: Classification of Weathering

The salinity was measured by a electrical conductivity test using the model 470 Portable Conductivity/TDS meter, giving an estimate of how many ions were in the solution i.e. the solution's salinity. First the sediments were left to stand at room temperature for 2 hours, then a solution for each sample was made up of 5 ml of sediment and 25 ml of de-ionised water in a test tube. This was shaken for one minute and left to stand for ten more following which, to take the reading, a probe was immersed into the supernatant solution (not the sediment), the probe having first been calibrated.

These calibrations are needed in the calculation for obtaining the salinity value – A Step-to-step guide:

1. Conductivity standard x 4 = X value
2. X value / 5 = Salinity value (for that sample)

Results

Observations

T1 and T2 start from the beach, made up of hard and soft sediment with sand sedge (*Cyperus conglomeratus*) and mangrove vegetation covered evenly. The sabkha by the beach was a prominent feature (and where the first sample was taken for T1). There was a depression higher than sea level that contained sediments and it had no vegetation cover. Moist patches on the surface were noted either from recent precipitation or from the high tide. GPS elevation levels were inaccurate due to changes in air pressure, a variable that had to be disregarded from the investigation.

Salinity

T1 shows the highest salinity levels (maximum 15,740 μs) which were found on the sabkha by the beach and some of the lowest readings were in the centre of the town. T2 shows a variety of readings but generally they are higher than T3 and T4, a cluster of medium values at the start (near beach) and along the main road the other side of the town (away from the coast). T3 shows clusters of high and low readings. The high readings are at the start (furthest south), nearest to the other sabkha and to the new housing development whilst the low readings are central. T4 has variable measurements throughout with no discernible trends. These values were used to plot a graph of the variations along a transect, and to zone the salinity levels on a scaled map of the area (see appendix - Figure 1). T2S9 salinity measurement was disregarded in the analysis as it became too diluted when using the conductivity meter.

The midway values (ranging from 8,220.04 μs - 1,012 μs) were found in an area near the coastline between the sabkhas and also along the main road out of the town, to the east, away from the coast.

The lowest values (ranging from 99.88 μs - 974.44 μs) were found in the central part of the town which was the highest point above sea level (unconfirmed by GPS readings

Buildings

Figure 2 (see appendix) shows that zones for the ages of buildings could be established. The oldest buildings (including the ancient settlement) were located in the central and north-western part of the town, close to the beach and the northern sabkha. The middle-aged buildings (50-100 years) were found along the main road near the central part of the town where some of the highest and lowest salinity values were. The young buildings (0-50 years) were found on the edge of the town by the main road away from the sabkhas' and beach, where there is a zone for medium salinity values. Construction was ongoing on the new houses and shops, nevertheless the structures already showed evidence of salt action.

The results of capillary action damage found on the houses examined along T3 and T4 showed that there was more damage for the west-facing walls, closely followed by those facing north.

Discussion

The highest salinity values (range from 51,740 µs - 12,580 µs) were found in either the sabkha by the beach (NW of the town) or near the southern sabkha. Since the sabkha is a major source of salt which will accumulates at or near the surface this is not surprising. There was a crust layer on top of the depression in the sabkha by the beach. The sand was damp but firm due to capillary moisture from the water-table probably about half a metre down with salt in solution. Salt grains can be driven directly against buildings or lodged in crevices and pores (particularly in damaged buildings) by the sea spray. When the salts reach the surface by either process, the salts will precipitate and the water evaporate. A powder on the surface of some of town buildings was detected, evidence of crystallisation and salt efflorscence. Once salt is in solution it can be transported through the materials and the rate of transfer is dependent upon the viscosity of the solution and the permeability of the material (Pel et al, 2004). This would enhance the loss of cohesion at the surface of the bricks (Lubelli et al, 2004).

The salty sea-spray and few buildings in number will have led to the midway salinity values near the beach, yet the zone by the main road could be due to the high quantity of sabkha deposits in building material. The materials used were bricks, mortar and most likely Portland cement (Cady 1986) as well as render, paint or pebble dash for the middle- and young-aged buildings. The use of Portland cement associates with the salinity values as the cement mixture would have consisted of local water and sabkha materials (sand) and so would have had high sodium chloride content. Portland cement is the most resourceful building material and is widely used. Cady (1986) states that premature deterioration of this highly used concrete in the Arabian Gulf region is a serious problem and is caused by salt weathering (and reinforcing steel rods).

At the central part of the town where the lowest conductivity readings were found the water table would have been deeper due to the area being the most elevated and therefore the height of the capillary fringe (from transported salts) would not have reached the surface. Only the buildings around the edge of the town built-up area would have been exposed to the sea spray and deflation from north to north-westerly winds that are common in that area (Goudie et al, 2000). The salinity concentrations along each of the transects correspond with the distribution of ages of buildings. Where there are high salinity readings, the locations are within middle-aged and more recent building zones. However, T1 did not relate to the distribution of ages absolutely as the readings between T1S9-11 were expected to be higher as they were located near a high salinity zone with middle-age buildings. This was perhaps due to its being in the most elevated part of the town (the red tower is located here), thus limiting weathering.

The oldest buildings were in the central part (formerly the island) and the north-western parts of the study area and the highest salinity results were found there. These old buildings (100 years+) have withstood the sea spray and capillary action, due to the building material being calcarenite (bioclastic limestone) which has a strong adherence to mortars and is stronger than the modern brick-mortar combination. This was proved by Cultrone et al (2007) who evaluated the porosity and the circulation of fluids inside different compositions of materials using hydric tests, mercury intrusion porosimetry and electron microscopy. The rough surface of the calcarenite blocks used in construction create a stronger adhesive bond with the mortar than is possible using bricks which are generally too smooth. This may explain why the oldest buildings have not experienced as much deterioration as some younger ones. Nevertheless because they are the oldest and as weathering is time dependant, some buildings had experienced a full range of weathering and some were even classified as 'rubble' on our weathering scale.

The intermediate age buildings were at the edge of the original island, along the main access road in and out of town, and the youngest buildings were clustered along the same road but, because of increased vehicle usage, were further away from the centre. The amount of damage in both sections was as expected bearing in mind the building materials used. As Charola (2000) explains, masonry materials are porous and are susceptible to deterioration by salts in the form of crystallisation and hydration produced pressures. Fitzner and Snethlage (1982) found that smaller capillaries and micropores are very prone to salt attack, especially when adjacent to each other. Though according to Putris and Mauthe (2001) crystal growth prefers larger pores, and in a bimodal size distribution, the smaller pores assist as solution reservoirs for the larger pores to grow crystals (Ruedrich et al, 2007). However, less resistant rocks with low tensile strength and changed volume induce stresses but the stresses from the crystal growth have to exceed the tensile strength before damage can occur (Ruedrich et al, 2007). The lower the porosity the better the cohesion of the material which would then have a higher tensile strength and more resistance to damage by crystallization; calcarenite has a lower porosity than bricks.

The environmental conditions of Jazirat al Hamra lead to repetitive wet-dry cycles which result in regular hydration and dehydration of the emplaced salts, exacerbated by high diurnal temperature changes (leading to expansion and contraction of the salts), coupled with unpredictable but high precipitation intensities which may wash further salts into the materials of structures. When the water table recedes after extreme evaporation, salts and chemical deposits such as chlorides and sulphates are left in the upper surface and these are very corrosive to construction materials (Erol 1989).

All of the buildings in the town had experienced some degree of weathering due to the presence of salts in the atmosphere and in the soils with shallow groundwater. The literature suggests what was actually observed, however, that intermediate-aged and modern buildings have suffered a relatively greater degree of deterioration from salt weathering due to the materials used (e.g. bricks and concrete).

To determine the mechanisms that were responsible for the damage, and to avoid assumptions, the samples of soil should have been analysed for the types of salts present. This would help to confirm which mechanisms (e.g. thermal contraction/expansion or chemical hydration) were taking place within the buildings and causing the wide range of damage. It is well known that different salts behave differently as they have different chemical properties (Chapman 1980; Cooke et al, 1993; Charola 2000). Sperling and Cooke (1980) state that the change of solubility by evaporation has a major influence on rates of rock disintegration from crystallization and hydration and some salts are more active in the change than others like sodium sulphate compared to sodium chloride. Repeated hydration (expansion) and dehydration (shrinkage) cycles are another process that causes damage due to the changes in volume (Rijnier et al, 2005). Sperling and Cooke (1980) and Ruedrich et al (2007) state that sodium chloride is not a hydrate unlike sodium sulphate and magnesium sulphate. Goudie and Watson (1984) suggest that crystallization is a significant process in its own right for certain salts such as sodium chloride. Evans (1970) states that hydration is important for carbonates and sulphates but is not associated with sodium chloride disintegration of rock. For the best interpretation the mechanisms should have been verified, however, suitable apparatus for salt determination was not available for use.

The height of damage to buildings from the ground up (cracking, discolouration, peeling of render, powdering and weathered render, exposing bricks and mortar) was used to classify weathering and to see if damage was influenced by aspect. The cracking is produced from repeated swelling and shrinkage which would be resisted by tall and heavy buildings but lead to excessive foundation pressures in lightweight structures of two or three stories (Khan and Hasnain, 1981). The capillary rise measurements are in accordance with Doornkamp et al (1980), as shown in figure 5, observed by the height of discolouration and powdering. East- and west-facing walls would have been expected to have the most weathering through experiencing stronger daily temperature intensities. The effect of this would be the encouragement of capillary transport and evaporation and therefore damage from crystallization observable along the walls. On average the highest measurements for the town were from the west (1.51 m) closely followed by the north (1.45 m). East had the least capillary fringe height at 0.93 m; this was not suggested by the literature. The results suggest that another factor besides the sun's position is more significant for capillary action. North and west aspects with the highest heights correlate with the north-north westerly winds experienced in the area according to Goudie et al (2000). The sea spray (deflation of sabkha salts) will penetrate the walls (Lubelli et al, 2004) and the more sea spray, the more potential penetration and damage is created. The winds would direct the sea spray north westerly and would hit the sides of the north and west facing walls. This supports why south and east, facing away from the coast, had the lowest results. The heights were from four walls of six buildings from a total of 58 (time prevented a statistical sample being covered) so the results may be misleading and consequently the sun's position may well have a significant role and the wind a lesser one.

Cooke et al (1993) suggest that knowing the groundwater composition, depth and thickness of the capillary fringe, in relation to the configuration of building foundations, enables better control and management the implementation and maintenance of new buildings. Cady (1986) suggests that the use of the lowest water/cement ratios mixtures, designing concrete structures to minimise stresses from thermal expansion and shrinking and using vapour barriers and coatings on concrete would decrease intensity of the damage from salt action. The constructive approach of using damp-proof courses (DPC) in Australia has been successful, whereas other treatments are less successful such as hard cement renders, damp-proof mortar additives, and ceramic tubes inserted into masonry as drying aids (NSW Heritage Office, 2004).

The choice of the appropriate traditional solution such as special mortars and restoration renderings is unclear as they regularly fail in purpose mainly due to the repair materials not being compatible with the already present substrate containing salt (Hees et al [www]). Hees and Brocken (2004) studied the effects of applying a 'treatment' to masonry substrates either before or after exposure to salts. This investigation was carried out by weighing the substrate during the drying process after application and revealed that surface treatments led to more damage being sustained. Even when salt exposure only followed treatment treatment more damage was sustained. Observations were not made of any modifications or preservation techniques of any buildings in the town during the present study, except for the re-rendering or painting of some surfaces of walls or a complete rebuild (such as with the red tower).

The aim of this investigation was to resolve the extent of damage to buildings that have ranged from being erected 6000 years ago to those still under construction in an environment that was likely to be affected by salt weathering. The subjective classification of damage to walls of all ages (only able to be determined by materials used) and salinity of soil were examined to set up zones of salinity and building ages of the town. The zones were compared to see if there was a relationship between the materials and salinity values as well as with location and aspect of the buildings. As shown, there is an association between all these factors and scientific explanations given. However the understanding of the results cannot be conclusive due to the lack of data collected for aspect, inability to collect in equal amounts for the different ages, not investigating the salt type and not confirming the construction material. This could not be helped due to constraints on time and equipment. Also the method of transects has not been used in previous studies examined which may have been helpful in developing this investigation. These factors therefore should be considered when future investigations take place on weathering damage at other building projects in Arabia.

Conclusions

The methodology employed (i.e. the use of transects in a number of directions) was designed to assess the overall damage to buildings from salt weathering. Using the GPS readings, the salinity levels and ages of buildings could be zoned on to maps making it clear for a link to be interpreted. The locations of these two features of the investigation relate to each other as the salinity values are influenced by construction materials used. The climate was considered to interact with the environment in key locations (the sabkhas, the beach and inland areas and, to a lesser extent, the aspect) to produce differences of salinity levels in soil and, probably, within the masonry, which was illustrated by the damage of walls examined. The findings clearly show that damage is unavoidable and should be tackled to conserve new developments expanding along this popular and demanding coastline. Techniques have been successful and should be contemplated in future plans and implementations in relation to the amount of financial investment going into these complexes. These complexes are also causing a regional and global impact as the coastline is becoming destabilised due to the dredging and reclamation (in parts) or to sediment movement caused by large engineering structures. The consequence would be the interruption of the longshore drift and therefore the lack of sustainability of coastal sediments leading to the decay of the coastline and the loss or migration of marine life.

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Appendix

Figure 1: Distribution of salinity levels

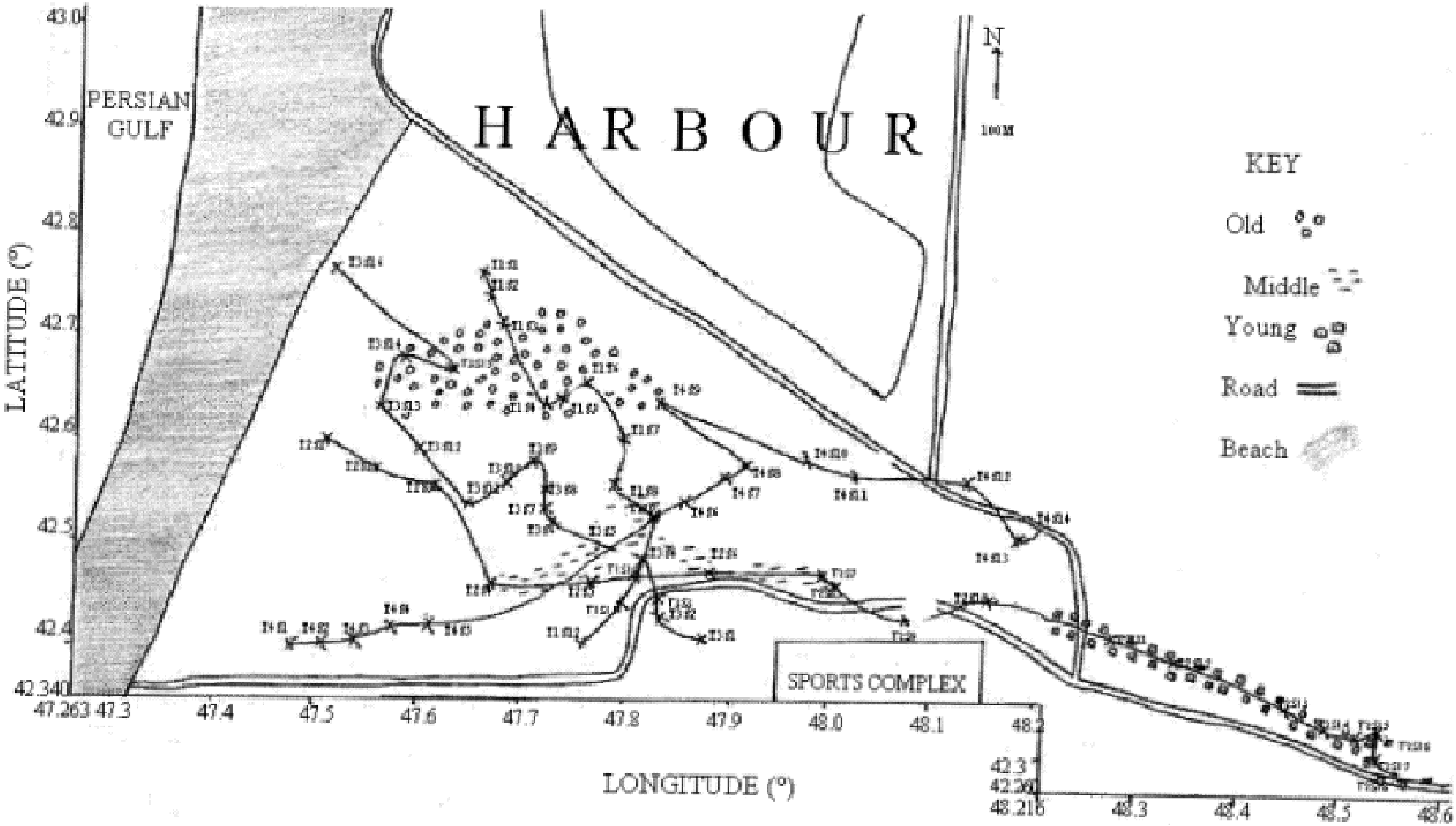

Figure 2: Distribution of Buildings