BURIED INFRASTRUCTURE IN SALINE SOILS: A REVIEW

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Abstract: Saline soils refer to a condition where high concentration of soluble salts exists in dry and wet environments found in different parts of the world. Infrastructure damage caused by saline groundwater costs millions of dollars for the rehabilitation and replacement of these infrastructures. Saline soils may occur naturally or induced by human activities. In arid regions and coastal areas salt usually accumulates inland due to shallow or rising saline groundwater. Change in soil salinity is known to affect the geotechnical properties of soils, which is generally manifested in changes in swelling potential, hydraulic conductivity, Atterberg limits, and soil permeability. This study summarizes the effects of saline soils on buried pipes. In addition, the study highlights the negative impact of the accumulation of soluble salts on the stability of soil structure. The effects of salt content on the geotechnical and mechanical behavior of soils in terms of compressibility and shear strength are also reviewed. Understanding the interaction between saline soil and subsurface structures will allow engineers to properly address design issues and propose proper mitigation techniques and management practices for the affected infrastructure.
Keywords: Saline soils; Environment; Buried infrastructure; Geotechnical properties.

1 INTRODUCTION

Saline soils refer to a condition where high concentration of soluble salts exists in dry environment found in different parts of the world. In drylands, this phenomenon may happen naturally due to erratic rainfall, high temperature, and evapotranspiration rates. Saline soil is considered an environmental challenge that may cause damage to urban infrastructure and cost millions of dollars for rehabilitation processes (Fatahi et al. 2011).This condition is generally caused by natural processes such as seawater intrusion into nearby lands that are below sea level (Fatahi et al. 2011). In addition, seawater intrusion may result from unstable weather condition caused by climate change and global warming, and it is one of the primary sources of salt accumulation in soil that affects subsurface water and threatens the ecosystem. Saline soils are considered contaminated and unsuitable for the growth of most crops (Paniconi et al. 2001). Salt intrusion can also result from human activities such as land clearing and aquaculture related activities (Fatahi et al. 2011). **Figure1** illustrates the effect of global warming and salt intrusion on river banks and levees in Japan (Komine, 2007a&b).

Salt is also used by cities and municipalities in cold regions (e.g. Canada, US, and Europe) for de-icing of roads and sidewalks during winter time. De-icing salts consist of intensive soluble salts like sodium chloride (NaCl) where the mobility of chlorine is very high. This saline solution can seep through the soil and negatively affect the quality of the groundwater in the region (Ružičić et al. 2018). It is, therefore, important to protect the quality of groundwater, which is a major source for drinking water and irrigation (Keesstra et al. 2012). On the other hand, saline soils can pose notable challenges to Civil Engineering projects, particularly for transportation infrastructure (Fatahi et al. 2011). Understanding of soil behavior under various environmental conditions is necessary to mitigate the possible issues associated with saline soils (Fang and Chaney, 2017). Thus, the incorporation of geotechnical, geochemical, and geo-environmental knowledge is essential for evaluating the influence of salinity on clayey soils deformation (Barbour and Yang, 1993; Di Maio, 1996).

Salt is nonreactive solute and it is non-complex compound compared to other substances that might be found in soil (Fang and Daniels, 2017). Sodium Chloride (NaCl) is the most predominant salts in saline soils, an experiment was conducted by Fatahi et al. (2011) to study the impact of NaCl salt on three soil specimens, including sand mixtures, bentonite, and kaolinite. These samples were collected from the east coast area of India. The results showed that the hydraulic conductivity of the tested soil increased with the increase of submergence time in salt solution.

This paper summaries the impact of soluble salts on the stability of soil structure. Emphasis is placed on conditions where sodium chloride (NaCl) is the predominant salt in the soil matrix. In addition, the effect of salt content on the geotechnical properties of soils is examined in terms of hydraulic conductivity, compressibility, and shear strength. In addition, the effects of saline soils on buried pipelines will be reviewed to help engineers to properly address design issues associated with these conditions and propose suitable mitigation techniques and management practices for the affected infrastructures.

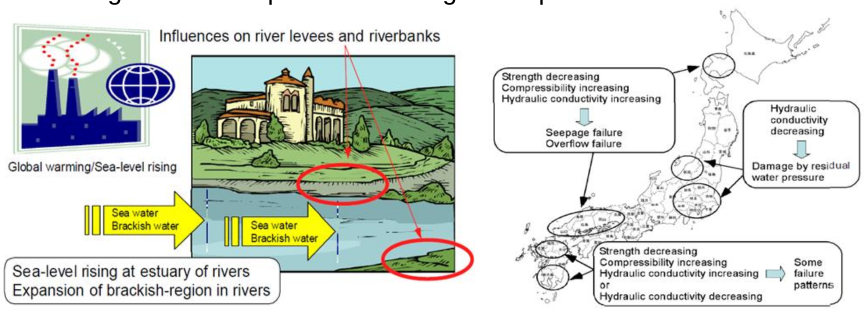


Figure 1: Damage patterns of river bank and levees due to sea-level rising in Japan (Komine, 2007a; Komine, 2007b).

2 LITERATURE REVIEW

2.1 The effect of salt on the geotechnical properties of soils

The geotechnical characteristics of contaminated soil either with salt or other chemicals can change due to chemical reactions between the contamination and mineral particles in soils. Liquid limit and plasticity index decreased as NaCl solution increased in soil (Nayak, Sunil, Shrihari, and Sivapullaiah, 2010). The increase of soil salinity was found to reduce the liquid limit of clayey soils. In addition, salt concentration was found to have an impact on the swelling potential of the soil (Castellanos et al., 2008).

2.1.1 Swelling potential and Hydraulic conductivity

Fang and Daniels (2017) reported that the swelling potential and hydraulic conductivity are highly influenced by the characteristics of the pore fluid. This section discusses the effect of soluble salts on the swelling potential and hydraulic conductivity of salt-affected soils. McNeal et al. (1966) proved that the swelling of clayey soils is negatively correlated with the relative hydraulic conductivity as illustrated in **Figure 2**. It was also found that high sodium content (SAR = Sodium Adsorption Ratio) promotes clay swelling under low concentration of soluble salts as shown in **Figure 3 (a).** McNeal et al. (1968) examined the relative hydraulic conductivity (HC) of saline soil under NaCl-CaCl2 solutions in the presence of exchangeable sodium ions. Results showed a decrease in HC with the increases in clay content when the clay is mixed with a mixture of salt solutions (see **Table 1**). Relative HC significantly decreased from the average initial value depending on the salt content in the solution. In addition, hydraulic conductivity was found to be highly influenced by the clay content of the tested soil.

Singh et al. (2011) conducted an experiment to study the hydraulic conductivity of saline sandy loam soil during leakage of NaCl and $CaCl_2$ salt solutions. Soil samples were saturated with salt solutions for 24 hours with five replicates of each salt solution. Plexiglass column (5.4×16 cm) was used to determine the hydraulic conductivity of the soil samples. **Figure 3 (b)** shows how the hydraulic conductivity changes over time where the hydraulic conductivity for the case of NaCl was 16 cm/day and 28 cm/day for $CaCl_2$. Results revealed that HC of Saline soil mixed with NaCl was drastically decreased over time, while lightly decreased under a mixture of salt solutions (Na2SO4, NaCl, Na2CO3, $CaCl_2$, CaCO3, and MgSO4). In addition, $CaCl_2$ increased HC of saline sandy loam soil over time. The study proved that the sodium ions have negative impacts on the soil structure, whereas Ca ions improves soil structure.

Table 1: Relative hydraulic conductivity (HC) of clayey soil mixed with salt solutions (NaCl - $CaCl_2$) in the presence of exchangeable sodium (SAR), (McNeal et al., 1968).

Average clay content (%)	Average initial HC (cm/hr)	SAR	Relative HC				
			800	200	50	12.5	3.13
			(meq/l)				
Group (1) - 5.7%	7.13						
		0	1.00	1.07	1.07	1.03	1.02
		25	1.00	.99	.99	.93	.89
		100	1.00	.96	.76	.38	.21
Group (2)- 16.2%	1.98						
		0	1.00	1.01	1.00	.98	.96
		25	1.00	1.00	.90	.62	0.26
		100	1.00	.76	.10	.00	.00
Group (3)- 48.5%	.523						
		0	1.00	1.06	1.00	.99	.94
		25	1.00	.84	.66	.20	0.01
		100	1.00	.33	.10	.00	.00

meq/l: milliequivalents of solute per litre of solution, SAR = Sodium Adsorption Ratio.

Mishra et al. (2008) investigated the influence of soluble salts of both NaCl and $CaCl_2$ on four types of bentonite clayey soils. Liquid limit and hydraulic conductivity of studied clayey soils were measured under different concentrations of salt solutions. Results revealed that the liquid limit of bentonite soil increased at low concentration of $CaCl_2$.Whereas, the liquid limit of bentonite clayey soils did not experience significant change at low concentration of low NaCl. In all cases, the hydraulic conductivity was found to decrease as the salt concentration decreased. It was concluded that calcium chloride ($CaCl_2$) has significant impacts on clayey soils as compared to sodium chloride (NaCl). On the other hand, the swelling potential increased under low concentration of a salt solution and high exchangeable sodium percentage (ESP) and was higher for NaCl solution as compared to $CaCl_2$ at the same concentration.

Subramani et al. (2005) demonstrated that the excessive amount of sodium ions in soil decreases the stability of the soil structure. Likewise, Keren and Ben-Hur (2003) explained that sodium ions reduce soil ability to form aggregate particles due to the increase of swelling potential. Chaudhari et al. (2014) found that the electrical conductivity of soil increases as salt concentration increases. This is generally associated with an increase in soil permeability that enhances the leakage of salt solutions to groundwater and thus, affects the quality of groundwater used for drinking and irrigation. Matthew and Akinyele (2014) conducted an experiment to investigate the relationship between two inorganic salt species (e.g. NaCl and Calcium sulphate Ca_2SO_4) and soil permeability. Soil samples were collected from south-western Nigeria to investigate the impact of inorganic salt solutions on soil permeability. The results showed that the increase in NaCl concentration increased soil permeability. However, the increase in Ca_2SO_4 concentration decreased soil permeability. This was attributed to the fact that calcium cations are able to form strong bonds between soil particles when attracted to adsorbed soil layer, whereas sodium cations (Na+) forms weak bonds between soil particles.

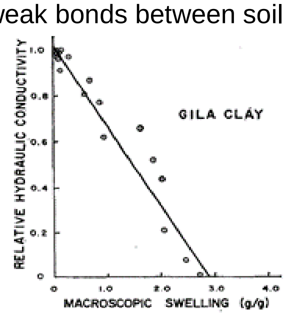
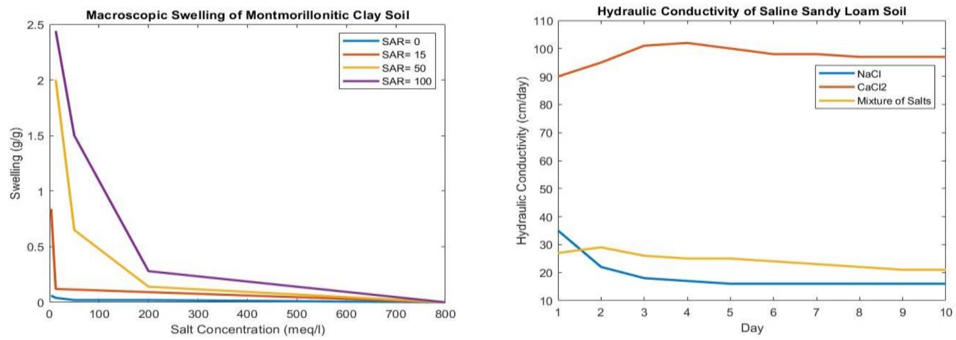


Figure 2. Macroscopic swelling for clayey soil versus relative hydraulic conductivity (McNeal et al., 1966).



(a) **(b)**

Figure 3: (a) Macroscopic Swelling potential of Gila clay soil under different sodium content. (Note: SAR= Sodium Adsorption Ratio =($\frac{Na^{+}}{\sqrt{\frac{1}{2}(ca^{2+}+Mg^{2+})}}$)). **(b)** Hydraulic conductivity of saline sandy loam soil over time during leaching of salt solutions (e.g. NaCl and $CaCl_2$) and mixture of salts.

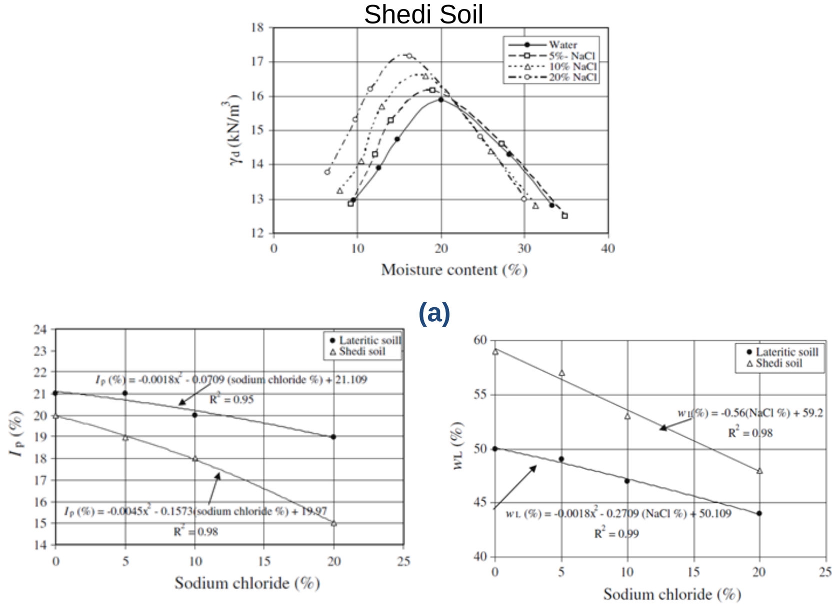
2.1.2 Density and Atterberg Limits

Nayak et al. (2010) conducted a study to explore the impact of salt water on the geotechnical properties of two types of soils (Lateritic and Shedi soils), including Atterberg limits, compaction characteristics, soil density, and chemical characteristics of the soils. The studied soil samples were collected from the west coast region of India and 0.5 N (N= eq/l) sodium chloride was added to soil samples to maintain a constant salt concentration. Soil samples were then mixed with different concentrations of sodium chloride. Results showed that optimum moisture content (OMC) of both types of soils decreased as the concentration of sodium chloride increased, **Table 2** shows a sample of the results obtained for Shedi soil. The maximum dry density of the soil increased with the increase in sodium chloride, as shown in **Figure 4 and Table 2**. The results also indicated that the increase in sodium chloride led to a decrease in liquid and plastic limits for both soils. It was concluded that the impact of NaCl salt was higher on Shedi soil than Lateric soil (see **Figure 4**).

Table 2: Soil properties of Shedi soil mixed with 0.5 N (N= eq/l) sodium solution (Nayak et al., 2010).

Shedi soil (No salt solution) G_S (2.65)			**Soil Mixed with Sodium chloride % by weight of soil**				
Atterberg limits			Sodium Chloride (%)	0%	5%	10%	20%
w_L (%)	w_P (%)	w_S (%)	Clay (%) (<2microns)	18	17	16	14
59	39	26	w_L (%)	59	57	53	48
Grain-size distribution			I_p (%)	20	19	18	15
Sand (%) (75 microns–4.75 mm)	Silt (%) (2–75 microns)	Clay (%) (<2 microns)	γ_d (KN/m^3)	15.9	16.2	16.6	17.2
59	23	18	OMC (%)	20.1	19	18	16.3
			K (cm/sec)	1.6 × 10^{-6}	1.63 × 10^{-6}	1.8 × 10^{-6}	2.6 × 10^{-6}
			e	0.75	0.81	0.92	1.10

G_S Specific gravity of soil solids, w_L Liquid limit, w_P Plastic limit, w_S Shrinkage limit, OMC: Optimum Moisture Content,
γ_d: Maximum dry density, *K* Hydraulic conductivity, I_p (plasticity index).



(a)

(b) (c)

Figure 4: Effect of NaCl on: **(a)** compaction characteristics of Shedi Soil; **(b)** liquid limit; and **(c)** plastic limit of Lateritic and Shedi Soils (Nayak et al., 2010).

2.1.3 Grain Size and Compressibility

Tiwari and Ajmera (2014) studied the variation in particle size and compressibility of three types of clayey soil (e.g. kaolinite, montmorillonite, and illite) treated with NaCl solution. The results indicated that montmorillonite was significantly aggregated after being treated with sodium chloride, thus compression indices, clay fraction and Atterberg limits were significantly reduced. They also found that the NaCl solution has a significant impact on the geotechnical properties of montmorillonite as compared to other types of soils. **Figure 5 (a)** shows the particle size distribution of soil treated with NaCl solution and those treated with distilled water (no salt solution). It is clear that soil particle size has changed after treating with NaCl solution. Soil samples were subjected to vertical pressure (384 kPa) and the vertical deformation was measured over time to evaluate the effect of NaCl solution on soil compressibility. **Figure 5 (b)** shows the change in compressibility of montmorillonite soil treated with NaCl as compared to other types of soils (kaolinite and illite). Compressibility of montmorillonite was found to decrease when the pore fluids contain saline water. Chen et al. (2000) found that the compression index of kaolinite and illite does not rely on the chemistry of pore fluid.

2.1.4 Shear strength

Moayed et al. (2011) carried out direct shear tests to study the shear strength of saline soil after and before soaking. Results showed that the shear strength of saline soil has significantly decreased after soaking. **Figure 6** shows that the shear strength of soaked saline soil has decreased by about 80%.

The effect of salt on the geotechnical properties of soil has been studied by several researchers (e.g. Yukselen-aksoy et al. 2008). The effect was found to generally depend on the type of clay minerals present in the soil. Different salt species were found to affect soil properties differently. For example potassium chloride (KCl) enhances the shear strength of clays, whereas sodium chloride can negatively affect the shear strength of soils. The difference between the non-sensitive clay and sensitive clay relies on the concentration of salt in the pore water. The cohesion and friction angle of soil were found to increase due to the addition of calcium to soils forming strong bonds between clay minerals. Thus, calcium and potassium have been used in various ground improvement techniques to improve the shear strength of soils. **Table 3** summarizes the effect of soluble salts on the geotechnical behavior of different types of soils.

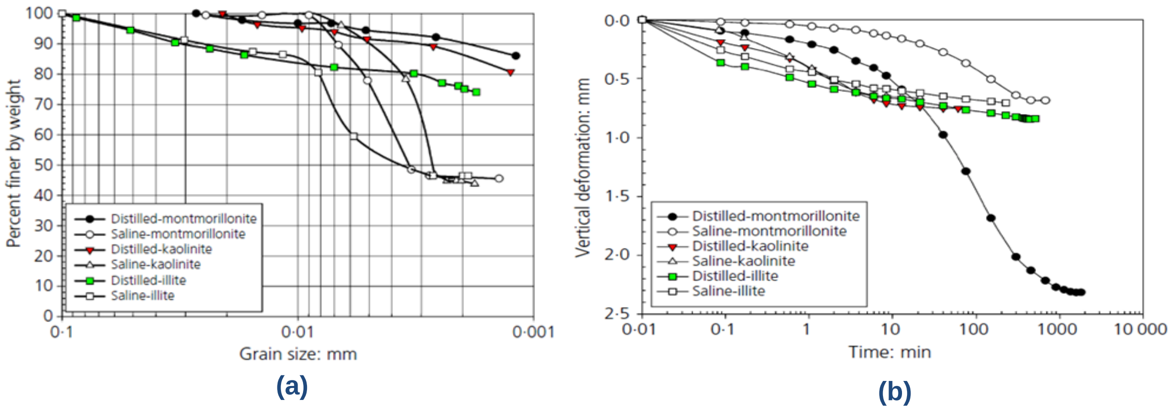


Figure 5: (a) Particle size distributions of different soil samples treated with NaCl solution **(b)** Changes in vertical deformation of treated and untreated soil samples with time (Tiwari and Ajmera, 2014).

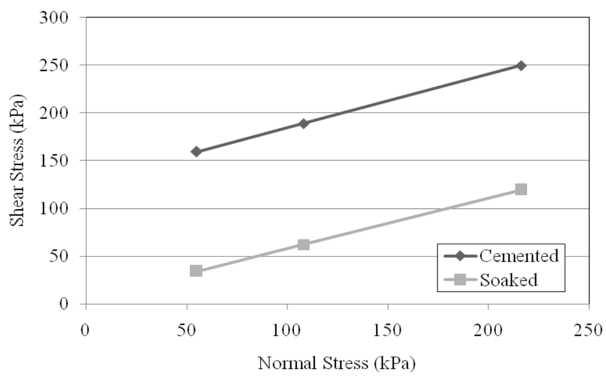


Figure 6: Soaking effect on shear strength of saline soil (Moayed et al., 2011).

Table 3: Summary of the effects of salinity on the geotechnical behavior of soil.

Reference	Type of applied salt solution to soil	Type of Soil	Geotechnical Properties	Results
McNeal et al. (1966)	Mixed salt solution ($NaCl-CaCl_2$)	Clayey soil	Swelling Relative HC	-Negative correlation between swelling potential and relative HC. -Swelling potential increased at low concentration of salt solutions and high sodium content
McNeal et al., (1968)	Mixed salt solution ($NaCl-CaCl_2$)	Clayey soil	Relative HC	-Relative HC decreased at low concentration of salt solutions and high clay content -Soil permeability decreased with a high content of clay and low concentration of mixed salt solutions
Singh et al., (2011)	NaCl CaCl2 Mixture of salt solutions (Na2SO4, NaCl, Na2CO3, CaCl2, CaCO3, MgSO4)	Saline sandy loam soil	HC	-HC significantly decreased over time when soil mixed with NaCl (sodium has negative impacts on soil structure) -HC decreased over time when soil mixed with a mixture of salt solutions -HC increased over time when soil mixed with $CaCl_2$ (Ca improves soil structure)
Mishra et al., (2008)	NaCl CaCl2	Bentonites clayey soils	HC Liquid limit	-low concentration of $CaCl_2$ increased the liquid limit of soil -low concentration of NaCl has no impact on the liquid limit of soil -Similar results to McNeal et al., (1968) and McNeal et al. (1966)
Matthew and Akinyele (2014)	NaCl Ca_2SO_4	Contaminated saline soil	Soil permeability	-Soil permeability increased with a increase in NaCl and decreased with the increase in Ca_2SO_4 -Ca^{2+} forms strong bonds whereas, Na^+ form weak bonds between soil particles when attracted to adsorbed soil layer.
Nayak et al., (2010)	NaCl	Saline Lateritic soil Shedi soil	Atterberg limits Soil Density Optimum Moisture Content (OMC)	-The maximum dry density of soil increased with salt solutions - Liquid and plastic limit decreased with salt solutions -OMC decreased with salt solutions
Tiwari and Ajmera (2014)	NaCl	Kaolinite, montmorillonite and illite clayey soils	Grain Size Compressibility	- Significant reduction in compressibility of treated montmorillonite soil with NaCl -Significant change in grain size of treated montmorillonite soil with NaCl
Moayed et al., (2011)	Mixture of soluble salts	Saline soil	Shear Strength	-Shear Strength significantly decreased after soaking

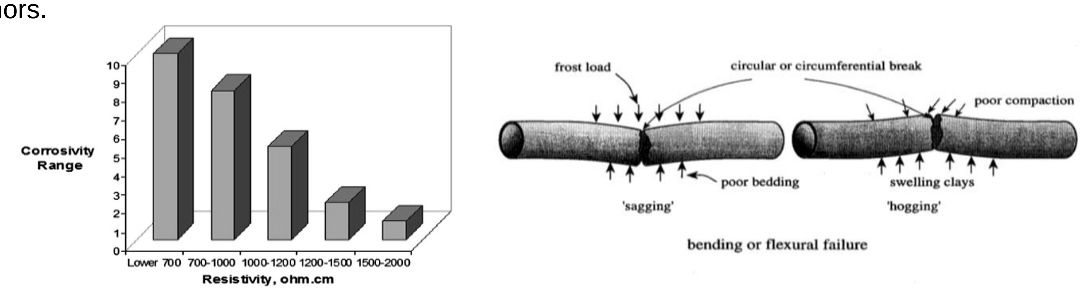
3 The interaction between Saline Soil and infrastructure

The characteristics of soils used as backfill material around buried pipelines can have an impact on the service life of the structure. Problems related to the quality of the backfill material may include corrosion of the pipeline, erosion of the backfill soils, and excessive movement. This can be exacerbated by the earth and live loads acting on buried infrastructure and can lead to pipe failure. Meguid and Youseef (2017) used expanded polystyrene (EPS) geofoam to reduce earth pressure on a buried structure. In addition, Meguid et al. (2018) indicated that using a soft inclusion made of tire-derived aggregate (TDA) within the backfill material can significantly reduce the earth pressure on rigid pipelines. Pipe corrosion, on the other hand, can develop due to several factors related to soil resistivity, pH value, reduction potential (redox), and soil moisture level. The presence of water in some types of soils may cause swelling, which imposes additional pressure on the buried structure. The interaction between soils with clay content and steel pipelines can cause corrosion and accelerate the deterioration process (Ismail and El-shamy 2009).

3.1 Saline Soil and corrosion of buried pipelines

Soil resistivity is known to decrease with the increase of soluble salt concentration. A study (Ismail and El-shamy 2009) showed that as the soil resistivity decreases the corrosion potential increases, particularly when in the presence of moisture (see **Figure 8 (a)**). Additionally, as mentioned previously, salt can accumulate in soil for many reasons including de-icing of roads, and brackish groundwater. Surveys have been conducted by American Water Work Association (AWWA) to investigate the root cause of failures of buried pipes. The results revealed that almost 70% of metal pipelines failed due to soil corrosion (Romer et al. 2004), as depicted in **Figure 9**. In another study (Hu and Cao, 2013), the impact of a 3% of NaCl solution on carbon steel pipeline has been investigated. Results indicated that corrosion rate was accelerated due to the existence of chloride ions in the soil.

Watermains are essential infrastructure in most developed countries. The failure/break of buried watermains generally happens due to soil movement, which induces longitudinal tensile stresses on the watermains. Tensile stresses could also develop if the clayey soils surrounding the pipe contain high percentage of saline mineral (e.g. sodium chloride). In addition, Rajani et al. (1996) found that failure of buried pipelines could develop due to additional longitudinal tensile stresses imposed on the pipelines resulting from the presence of swelling soils or poor bedding support, as shown in **Figure 8 (b)** (Rajani et al., 1996). Therefore, the increase of salt concentrations in soil enhances the swelling potential of soil and consequently increases the chance of pipelines failure. **Figure 10** Shows a schematic of the different variables that may affect pipe failure. These factors are the subject of expanded investigation by the authors.



(a) **(b)**

Figure 8: (a) The increase of soil resistivity with the increase of salt concentrations in soil leads to increase the potential of soil corrosion (Ismail and El-shamy 2009); **(b)** The failure of water mains pipelines due to poor bedding support and clay swelling (Rajani et al. 1996).

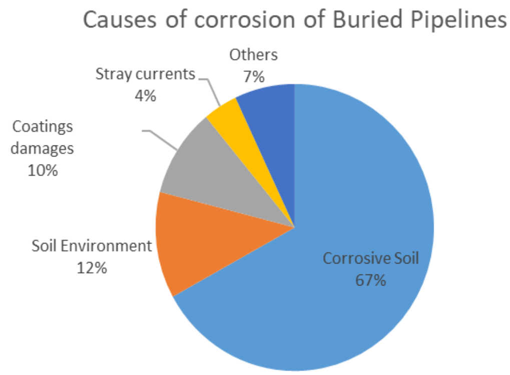


Figure 9: Factors affecting the failure of metal buried pipeline due to corrosion (Romer et al. 2004).

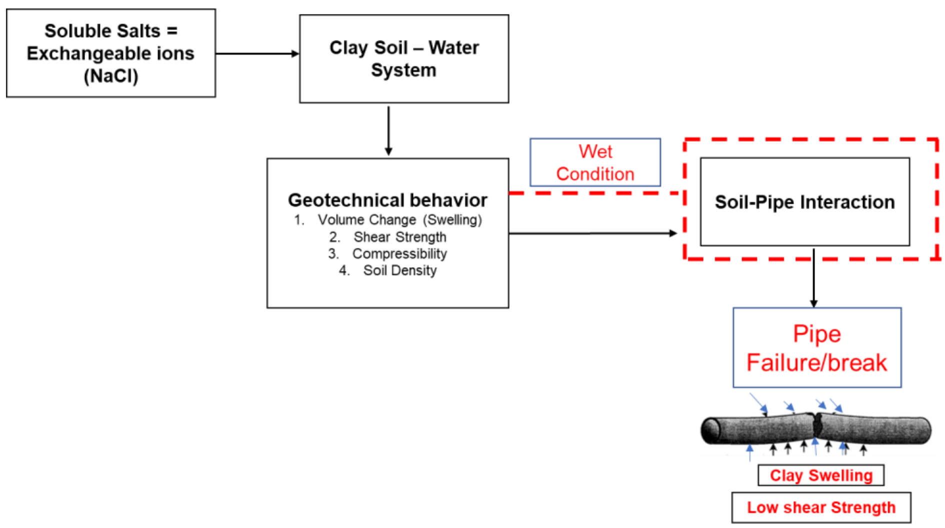


Figure 10. Interaction between Saline Soil- Buried Infrastructure.

3.2 The Cost of Rehabilitation Project for Buried Pipelines in Montreal City

Buried pipelines are expected to have a long lifetime between 50 to 100 years. Buried pipelines cost millions of dollars for replacements and rehabilitation depends on the size of the pipelines network, operation processes, and materials, etc. On the other hand, rehabilitation and replacement of deteriorated buried pipelines are highly expensive. The water distribution network in Montreal covers over 5000 km of buried pipeline. The cost of rehabilitation project in Montreal city costs $ 671,299, with direct costs (general costs) identified to be $ 540,000, indirect (e.g. pavement damage, compensation and tax rebates) and external (e.g. property damage, accidental injury and death, and air pollution) costs were assumed to be $ 4,126 and $ 127,173, respectively. Indirect and external costs represent nearly 20 percent of the total cost, whereas direct costs represent 80 percent of the total costs (Ormsby, 2009).

4 Summary and Conclusions

This paper summarized the impact of the accumulation of soluble salts on the properties of soils interacting with buried structures. Emphasis was placed on sodium and calcium chloride salts that are known to be predominant among different salt species. The paper covered the effect of salt content on the hydraulic conductivity, compressibility, Atterberg limits and shear strength of the affected soils. In addition, the interaction between saline soil and buried pipelines was briefly discussed.

Buried pipelines are crucial to Cities around the world as they carry drinking water, transport energy resources (e.g. oil and gas) and transfer wastewater to treatment plants. Defining the environmental conditions that may lead to pipeline corrosion including rising sea level and global warming is necessary to geotechnical and geo-environmental Engineers. Based on the limited review performed on this subject, the following conclusions can be made:

- Sodium ions have negative effects on soil proprieties as they enhance the swelling potential of clays and reduces the shear strength of soil.
- The effect of sodium chloride on a given soil is correlated with the clay content in that soil.
- Soluble salt (e.g. NaCl) increases the potential of clay swelling which may lead to deterioration/corrosion of buried pipelines.
- The change in soil properties due to the introduction of salts generally depend on the nature of soil as well as the type of soluble salt.
- The geotechnical properties of saline soils can significantly change under wet condition.

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