Flow Characteristics through Granular Soil Influenced by Saline Water Intrusion: A Laboratory Investigation

Sudip Basack [1]*, Ghritartha Goswami [2], Hadi Khabbaz [3], Moses Karakouzian [4]

[1] Professor and Principal, Elitte College of Engineering, Affiliated: MAKA University of Technology, Kolkata, India.

[2] Research Associate, North Eastern Regional Institute of Science and Technology, Nirjuli, Arunachal Pradesh, India.

[3] Deputy Head Research, Geotechnical Engineering Division, School of Civil and Environmental Engineering, University of Technology, Sydney, Australia.

[4] Professor of Civil Engineering, University of Nevada, Las Vegas, United States.

Abstract

The coastal geoenvironment initiates saline water intrusion into the freshwater aquifers, producing a geohydraulic problem. Such intrusion not only contaminates the fresh groundwater resources, making them unsuitable for human use, but also alters the hydraulic conductivity of the aquifer materials, which affects the coastal groundwater flow, influencing the water resources planning and management. Past investigations reveal that the groundwater flow can be linear or nonlinear depending upon the hydraulic gradient. Thus, the coefficients of nonlinear hydraulic conductivities are affected by saltwater intrusion. The present study focuses on an in-depth laboratory investigation into the influence of saltwater submergence on the nonlinear flow characteristics through granular soil. The fine sand samples have been submerged under saline water of specified concentrations for a specific duration, and the alteration in their nonlinear geohydraulic properties has been studied. It is observed that the flow characteristics through fine sand are significantly affected by the period of submergence and saline concentration. Appropriate analyses of the test results are performed to interpret the experimental data, and relevant conclusions are drawn therefrom. The novelty of this study is an in-depth analysis of nonlinear flow characterization affected by saline water intrusion.

Keywords: Hydraulic Conductivity; Saline Water Intrusion; Sand; Darcy Flow; Forchheimer Flow.

1. Introduction

The term salinity may be defined as the total concentration of all soluble salts in a specified sample. Seawater consists of chlorides, sulphates, and carbonates of sodium, calcium, and magnesium, with the most common salt being sodium chloride [1, 2]. The increasing population in coastal localities worldwide demands enhancement of freshwater extraction in those regions initiating saltwater interface to advance towards the aquifers, producing saline water intrusion [3]. Such intrusion not only contaminates coastal fresh groundwater resources remarkably making it unsuitable for consumption for domestic, irrigation, and industry usages, but also alters the geotechnical and geohydraulic properties of the aquifer materials affecting their flow characteristics, influencing the pumping and other engineering activities [4-11].

Researchers have studied for decades to understand the complexity of saline water intrusion into coastal aquifers and to find out the possible solutions for its prevention. Commencing from theoretical analyses [12-16], laboratory studies [1, 17-23], and field-based investigations [24-29], the subject has undergone significant advancements. Several contributions to coastal groundwater management [5, 30–34] are worthy of note as well. Although the alteration in geotechnical and geo-hydraulic properties of aquifer materials due to prolonged saltwater intrusion affects the flow characteristics, thereby influencing coastal groundwater management and modelling significantly, the investigations to cover this study area have been rather limited [35]. Even a few recent contributions in the last couple of years have not covered this important study aspect [36-39].

Saline water intrusion into the fresh water aquifers initiated in the coastal environment produces a significant alteration in the geotechnical and geohydraulic properties of the aquifer materials, producing a change in the flow pattern through the porous media. It is well established that the flow pattern may be linear or nonlinear, depending upon the induced hydraulic gradient. The transition from linear to nonlinear occurs whenever the hydraulic gradient increases from low to high. Essentially, the linear and nonlinear hydraulic conductivities are affected by the prolonged exposure of porous media to saltwater. The current investigation focuses on an in-depth study on the influence of saltwater exposure on such linear and nonlinear flow through sand, a natural porous medium. The linear and nonlinear hydraulic conductivities, and the critical values of hydraulic gradient and flow velocities were determined from graphical analysis of test data, and the important interpretations were found. In the previous publication [11], the authors carried out a laboratory-based investigation on the influence of saltwater exposure on several geotechnical properties of sand, more specifically specific gravity, dry densities, and linear hydraulic conductivity. Thus, the previous study was incomplete due to the absence of nonlinear flow. The current investigation has attempted to bridge-up this research gap. In the revised manuscript, the relevant clarification has been added.

The research methodology adopted in this study includes a review of literature, the establishment of theoretical correlations, collection of samples, calibration of test set-up, laboratory experimentations, analysis and interpretations. The relevant flowchart of execution is presented in Figure 1.
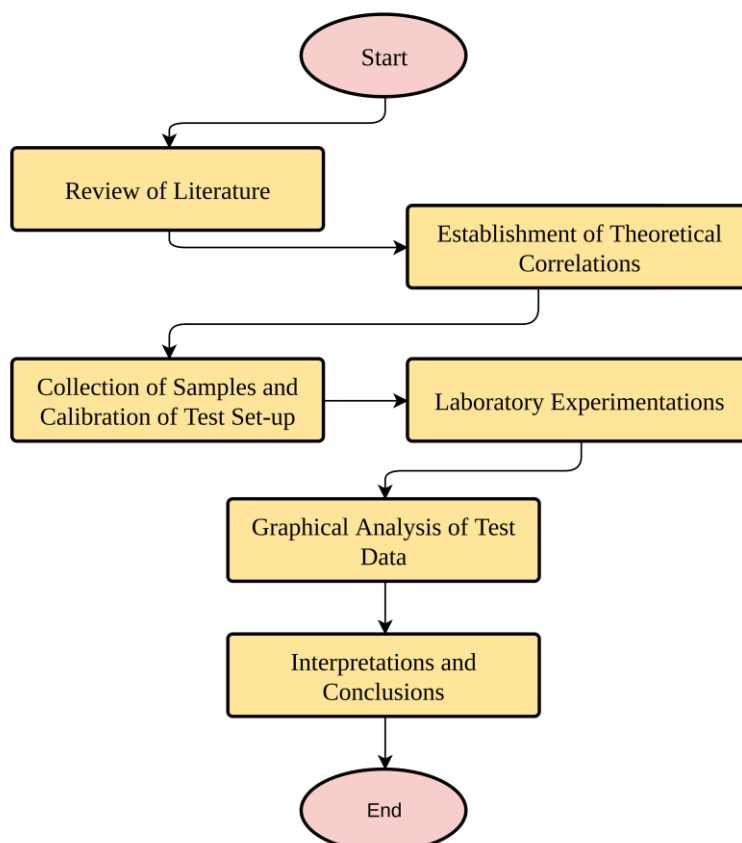

Figure 1. Flowchart of the research methodology employed in this study

2. Theoretical Correlations

The basic mathematical correlations relevant to flow through porous medium have been presented herein. Referring to Figure 2, where a steady and uniform fluid flow occurs through a soil mass with a length of L and a cross-sectional area of A under a net head of h, the net discharge being Q, the flow characteristics may be linear or non-linear, depending on the magnitude of hydraulic gradient [40].
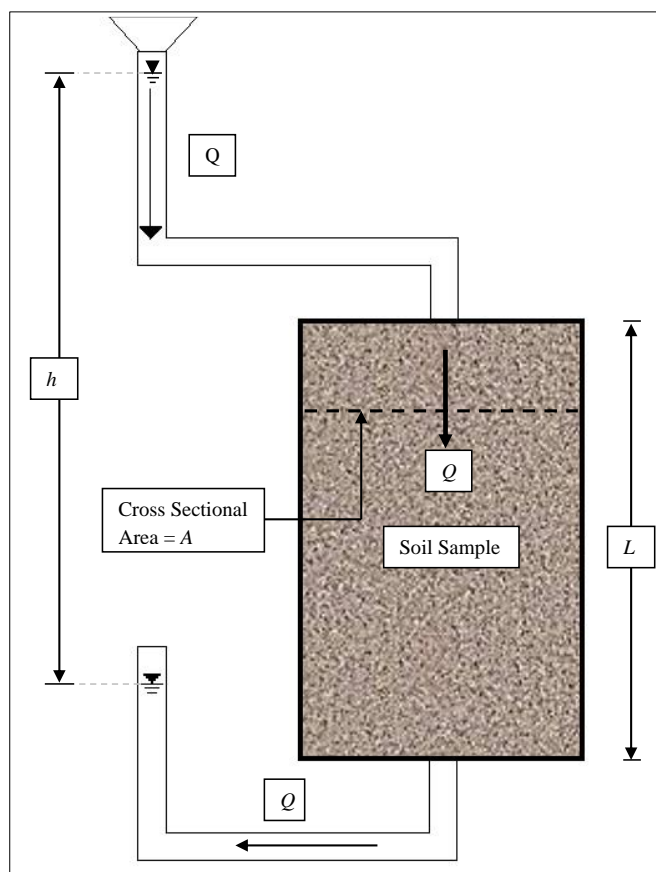
Figure 2. Steady and uniform flow through granular soil

For the lower hydraulic gradient, the flow is linear and following the applicability of Darcy's law of permeability Darcy [41], the following conventional correlation holds sound:

$$v = \frac{Q}{A} = k \frac{\Delta h}{\Delta L} \tag{1}$$

where v is the average flow velocity through the soil mass and k is termed herein as the coefficient of linear hydraulic conductivity, the dimension of which is LT^{-1}. Rearranging the terms, the above Equation is re-written in terms of the hydraulic gradient i ($= \Delta h / \Delta L$) as:

$$i = \frac{1}{k} v \tag{2}$$

For the greater magnitude of hydraulic gradient, on the other hand, the non-linear flow takes place, where Forchheimer's Equation [42] is valid. The relevant correlation is given by:

$$i = \frac{1}{k_1} v + \frac{1}{k_2^2} v^2 \tag{3}$$

where, k_1 and k_2 are denoted hereby as the first and the second coefficients of non-linear hydraulic conductivities, where the dimensions of them are LT^{-1}.

The linear and non-linear hydraulic conductivities are essentially intrinsic soil parameters. While Equation 2, represents a linear correlation between the hydraulic gradient and the average flow velocity, Equation 3 implies a parabolic variation. The point of intersection between the straight line and the parabola represents the critical point where the flow changes from linear to non-linear and vice versa. Eliminating the parameter i from Equations 2 and 3, the critical velocity (v_{cr}) is evaluated as:

$$v_{cr} = k_2^2 \left(\frac{1}{k} - \frac{1}{k_1} \right) \tag{4}$$

3. Experimental Program

The laboratory investigations have been conducted to study the influence of prolonged saltwater submergence on the geo-hydraulic properties of aquifer material relevant to the coastal environment. Locally available fine sand and rock salt samples have been used to carry out the tests.

3.1. Sand

Yellowish river sand available in the local market has been used to perform the experiments. The sample passed through a 75 µm sieve and retained by 425 µm sieve are used for the tests. Based on the sieve analysis conducted, the sample is uniformly graded fine sand [43] with the values of the coefficients of uniformity and curvature as Cu = 1.63 and Cc = 1.50, respectively. The particle size distribution of this soil is presented in Figure 3. Several routine tests were performed in the laboratory to find out the specific gravity, the dry densities, and the shear strength parameters of the sample. The appropriate values of these geotechnical properties are summarized in Table 1.
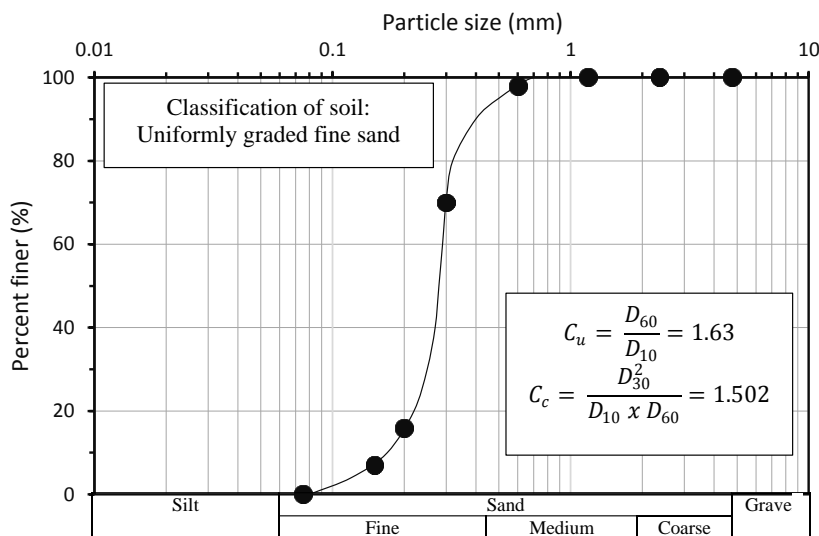

Figure 3. Particle size distribution of the yellowish river sand

Table 1. Geotechnical properties of fine sand prior to saltwater submergence

Geotechnical Properties	Values
Uniformity coefficient, Cu	1.63
Coefficient of curvature, Cc	1.50
Specific gravity of sand particles, G	2.67
Maximum dry density (γ_d^{max})	18.7kN/m³
Minimum dry density (γ_d^{min})	15.6 kN/m³
Effective cohesion*, c	0
Effective friction angle*, ϕ	30°
Coefficient of permeability*, k	1.17×10^{-8} m/s

* Note: All tests have been conducted at a relative density of 51%.

3.2. Saline Water

Locally available rock salt was dissolved in distilled water in appropriate proportion to prepare the saline water sample. Chemical analysis conducted specified the predominant presence of Sodium Chloride (98% by weight), with traces of sulphates, potassium, and calcium.

The available literature suggests that the seawater in most places around the world has an average value of the salt concentration of 30,000 – 35,000 ppm, although the saline water has been classified as mild (1,000 - 3,000 ppm), moderate (3,000 – 10,000 ppm) and high (10,000 – 35,000 ppm), based on its salt concentration [44]. Based on these ranges, the standard saline water solution is prepared by dissolving the salt weighing 5 gm in a liter of distilled water, the saline concentration being S = 5,000 ppm [45]. This standardization has been used to prepare the saline water sample with concentrations of 2S, 4S, 6S, and 8S.

The dry sand samples have been submerged in saltwater (see Figure 4) at specific concentrations for a specified period of submergence (T_s), as denoted in Table 2. At the end of the submergence, the samples were withdrawn from the solutions and oven-dried for 24 hours to carry out the experiments.

Figure 4. Soil sample submerged in saltwater

Table 2. Experimental schedule

Period of submergence Ts (days)	Saline concentration Based on S*
1, 3, 7, 14, 21, 28	2S
	4S
	6S
	8S

* S ≡ 5,000 ppm

3.3. Laboratory Tests

Appropriate laboratory tests were conducted to determine the values of specific gravity, dry densities, shear strength parameters, and permeability of the fine sand sample prior to the submergence. The specific gravity of soil particles was determined by employing the pycnometric tests [46]. The maximum and minimum dry densities of sand were found by the vibratory table method and the rainfall technique [47, 48]. The shear strength parameters of sand were found by direct shear test [49]. The locations of sample collection and laboratory tests are from Jorhat, India, shown below in the map (Figure 5).
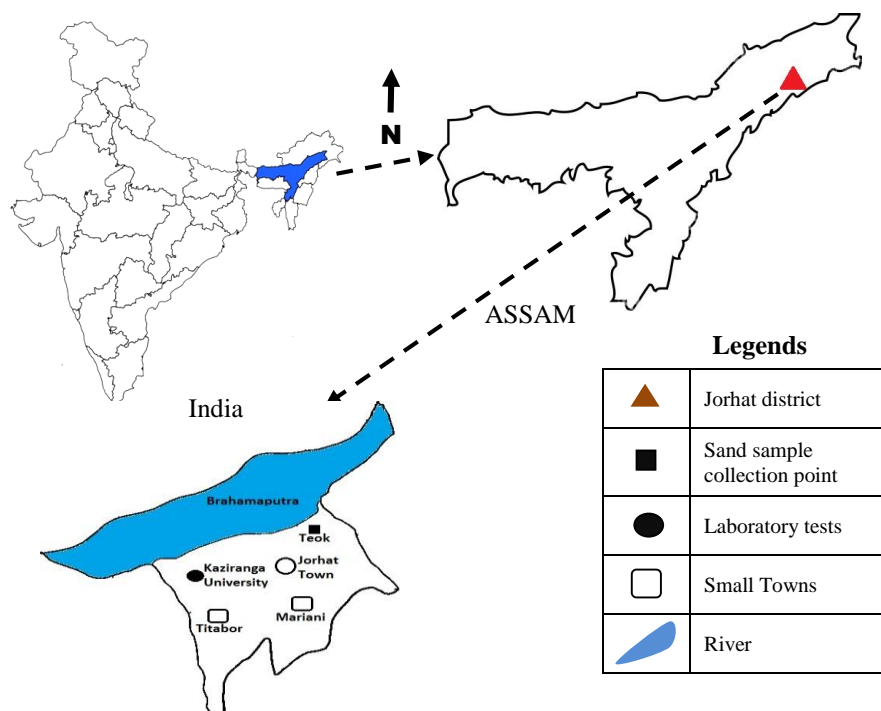

Figure 5. Location of the study area

The hydraulic conductivity of soil was determined using a falling head permeameter [50]. The diagrams of the apparatus are portrayed in Figure 6. The dimensions of the permeameter are as follows:

Cross-sectional area of the standpipe, $a = 314 \times 10^{-6}$ m^2

The cross-sectional area of the soil mass in the mould, $A = 127 \times 10^{-4}$ m^2

Length of the soil mass in the mould, $L = 0.127$ m

The shear strength and permeability tests were conducted at a relative density of 51%.
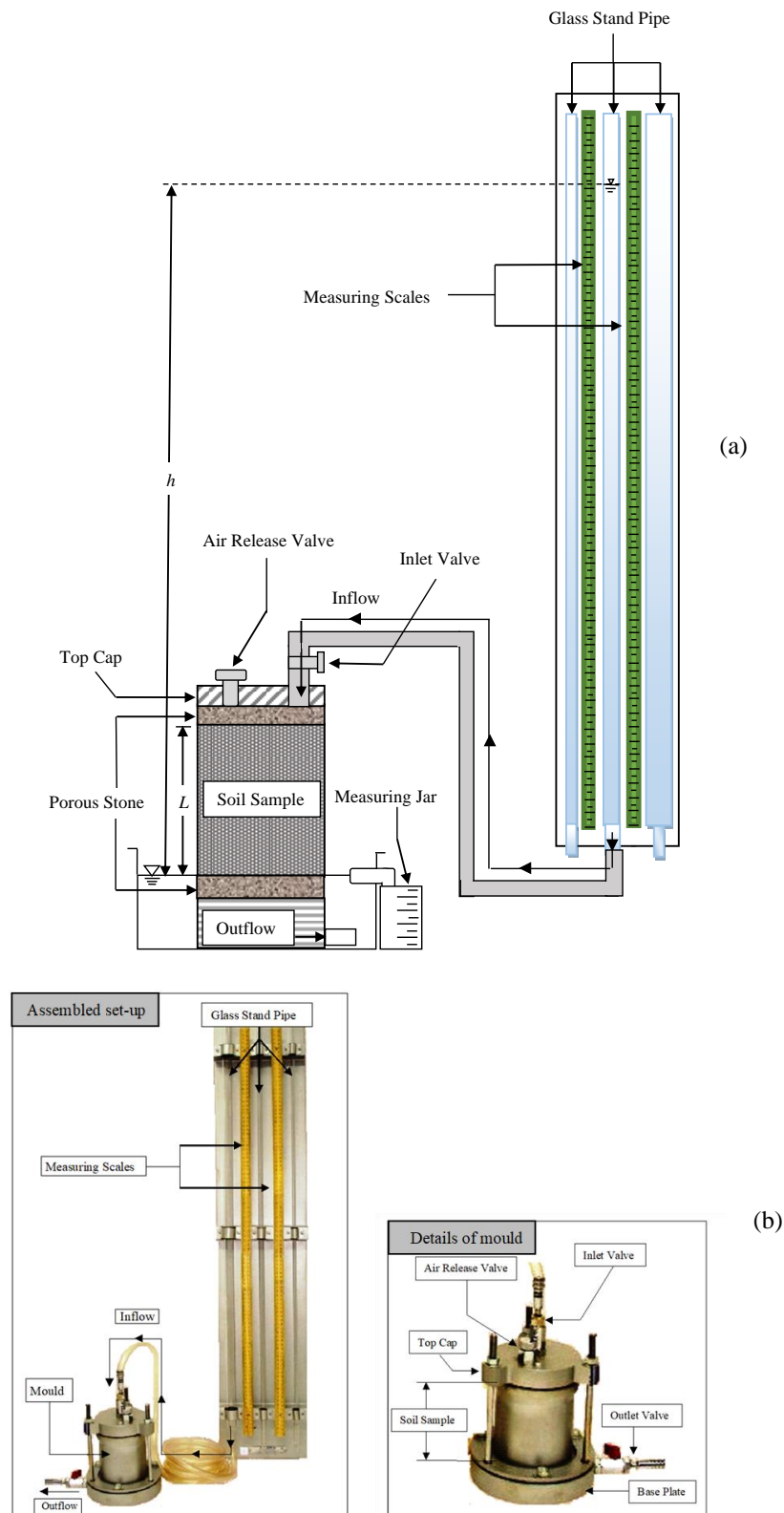
Figure 6. Falling head permeameter: (a) schematic diagram, and (b) photographic view

4. Results and Discussion

The variation of the coefficients of hydraulic conductivity of the sample with the period of submergence and saline concentration with respect to their relevant values prior to submergence have been studied. The experimental results and their analyses and interpretations have been presented in this section.

4.1. Evaluation of Coefficients of Hydraulic Conductivity

A typical plot of h versus the elapsed time t is depicted by direct use of the test data from the permeameter for the pre-submergence stage as shown in Figure 7. The observed curve is found to be hyperbolic with ascending slope and the value of h diminished at $t = 7200$ s. The test data have been utilized to study the variation of the hydraulic gradient i versus the average flow velocity v, as presented in Figure 8. The parameter v has been evaluated using the following correlation.

$$v = -\frac{a}{A}\left(\frac{dh}{dt}\right) \tag{5}$$

where a is the inner cross-sectional area of the inlet standpipe and A is the cross-sectional area of the soil mass in the permeameter mould. Expressing Equation 6 in finite difference form, the average flow velocity through the soil mass is given by [8]:

$$v_j = \frac{a}{A}\left(\frac{h_{j-1} - h_{j+1}}{t_{j+1} - t_{j-1}}\right) \tag{6}$$

where, v_j, h_j, and t_j are the values of the parameters v, h, and t at the jth time instant respectively
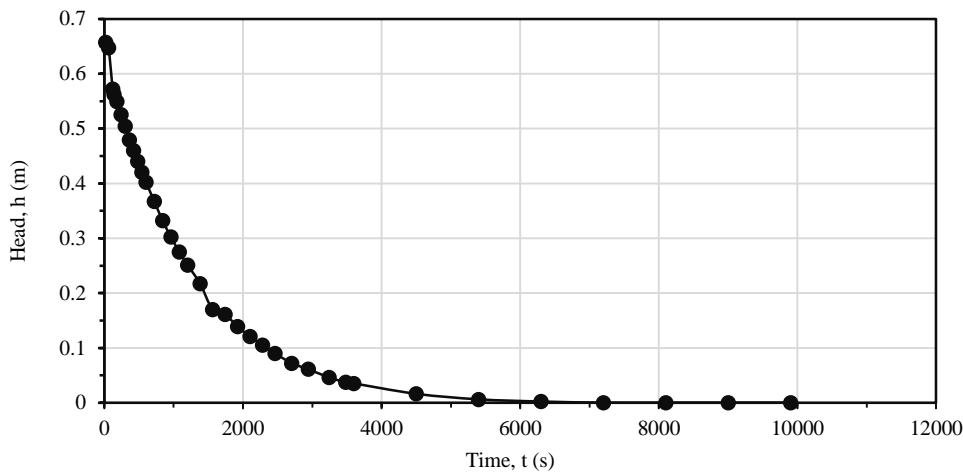

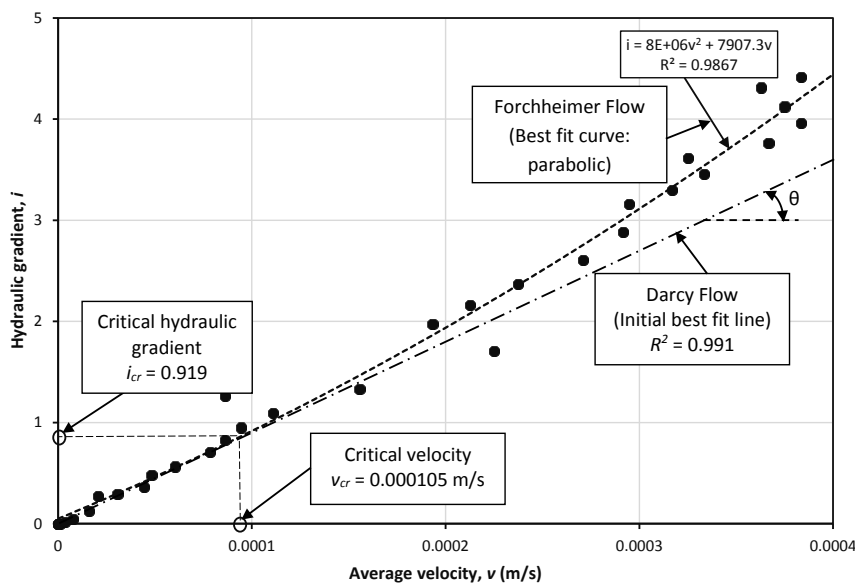**Figure 7. Test data of head versus time for pre-submerged soil**

Figure 8. Variation of hydraulic gradient with average flow velocity for pre-submerged soil

For lower values of hydraulic gradient, the flow through soil is expected to be linear, hence Equation 2 is applicable and the best-fit line passes through the origin. For higher values of hydraulic gradient, on the other hand, Equation 3 holds good due to non-linear flow and the best-fit curve is essentially parabolic with ascending slope. From the equations of the best-fit line and curve, the values of the coefficients of linear and non-linear hydraulic conductivity are estimated as:

$k = 1/\tan \theta = 1.143 \times 10^{-4}$ m/s

$k_1 = 1/7907.3 = 1.265 \times 10^{-4}$ m/s

$k_2 = 1/\sqrt{8.0 \times 10^6} = 3.536 \times 10^{-4}$ m /s

The values of v_{cr} and i_{cr} are evaluated from Equations 4 and 5 as: $v_{cr} = 1.05 \times 10^{-4}$ m/s, $i_{cr} = 0.919$.

Since the above values correspond to the pre-submerged soil, the parameters are denoted herein as k^0, k_1^0, k_2^0, v_{cr}^0, and i_{cr}^0. Following the same procedure, the values of the above parameters are determined for the soil submerged in saltwater at a specified saline concentration for a specified period of submergence.

4.2. Influence of Period of Submergence

The variation of linear coefficient of permeability with the period of submergence is shown in Figure 9, the parameter k has been normalized by k^0. With the saline concentration varying in the range of 2S– 8S (i.e., 10,000 – 40,000 ppm) and the period of submergence T_s ranging from1 -28 days, the value of k/k^0 is observed to vary in the range of 0.9–1.15. Initially, the value of k/k^0 is found to increase fairly linearly till a peak is attained and thereafter decreased following a curvilinear pattern. The peak is observed to attain at $T_s = 14$ days and the values of k/k^0 at this peak varied from 1.07 to 1.1. Also, a point of contra-flexure is observed at $T_s = 21$ days. A stabilizing tendency has been noted for $T_s \geq 28$ days. The possible reason for such variation is the progressive decomposition of sand particles at the initial stage, initiating an enhancement of porosity, which in turn increased the flow velocity through the soil mass. According to Tchistiakov [51], at the post-peak stage, the probable occurrence of a partial blockage of inter-particle pore space by the adsorbed saltwater produced an opposite phenomenon).
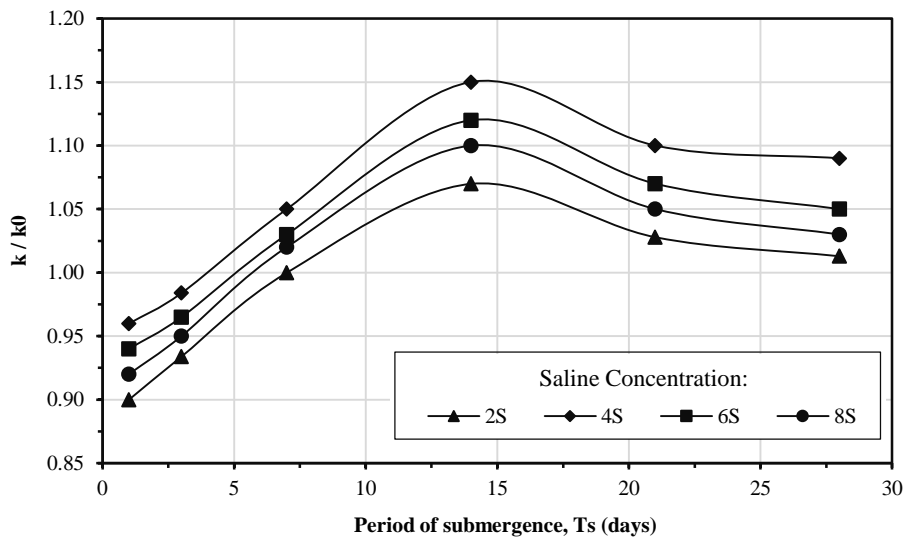

Figure 9. Variation of normalized permeability coefficient (k/k_0) with duration of submergence (T_s)

The variation of the coefficients of non-linear hydraulic conductivity with the period of submergence is portrayed in Fig.10. The plots of k_1/k_1^0 versus T_s are presented in Figure 10-a. Variation of the coefficients of non-linear hydraulic conductivities (k_1 and k_2) with period of submergence (T_s) is portrayed in Figures 10-a and 10-b, respectively. The coefficients are normalized by k_1^0 and k_2^0 , i.e., their relevant values corresponding to freshwater flow. As observed, the parameters k_1 and k_2 varied in the ranges of $0.84 < k_1/k_1^0 < 1.13$ and $0.7 < k_2/k_2^0 < 2.45$, as the period of submergence and salinity varied in the ranges of 1-28 days and 2S-8S, respectively. The parameter k_1 was found to increase with T_s, the pattern of variation being curvilinear with descending slope. Also, the curves progressively converged with increasing saline concentration. Similarly, the variation of k_2/k_2^0 with T_s is plotted in Figure 10-b. For the submergence period of 1-28 days and saline concentration ranging between 2S to 4S, the second coefficient of non-linear hydraulic conductivity is found to vary in the range of $0.74 \leq k_2/k_2^0 \leq 2.44$. The value of k_2 has been found to decrease with increasing T_s curvilinearly with ascending slope. A sharp reduction in the value of k_2/k_2^0 is observed for T_s ranging between 1-7 days, followed by a stabilizing tendency.
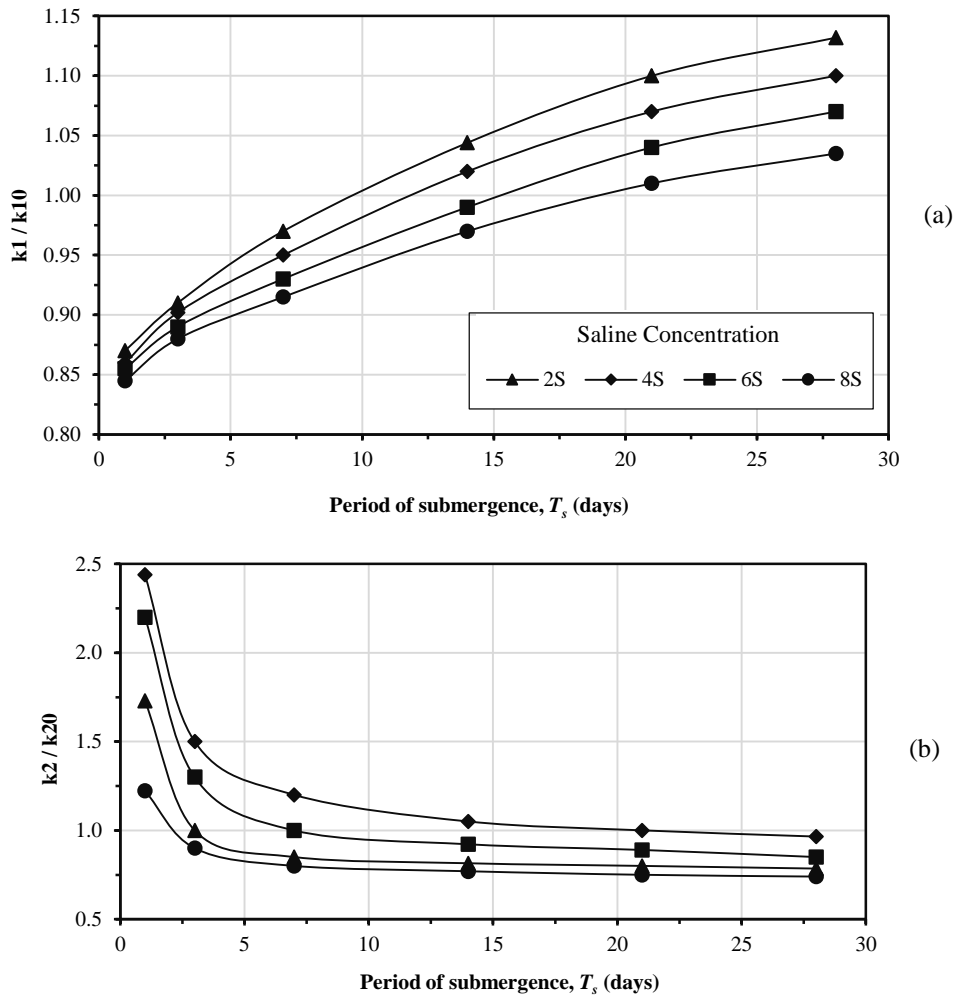
Figure 10. Variation of coefficients of non-linear hydraulic conductivity with T_s in case of: (a) the first coefficient, and (b) the second coefficient

Figure 11-a depicts the variation of i_{cr}/i_{cr}^0 with T_s. As observed, the value of normalized critical hydraulic gradient varied in the range of $0.875 \leq i_{cr}/i_{cr}^0 \leq 1.58$ for the period of submergence varying from 1-28 days and saline concentration ranging between $2S$ to $4S$, the pattern of variation being curvilinear. With increasing T_s, the parameter i_{cr}/i_{cr}^0 initially increased with descending slope till a peak is attained and thereafter decreases. The peak is observed at $T_s = 14$ days, with the corresponding value ranging from 1.464 - 1.581. The plots of v_{cr}/v_{cr}^0 versus T_s are shown in Figure 11-b. The value of normalized critical flow velocity through the soil mass is observed to vary in the range of $0.57 \leq v_{cr}/v_{cr}^0 \leq 1.4$ for the experimental ranges of T_s and saline concentration, the pattern of variation being curvilinear. With increasing T_s, the value of v_{cr}/v_{cr}^0 decreased with descending slope till a minimum value (ranging from 0.57 - 0.918) was attained at $T_s = 14$ days, after which the parameter increased.
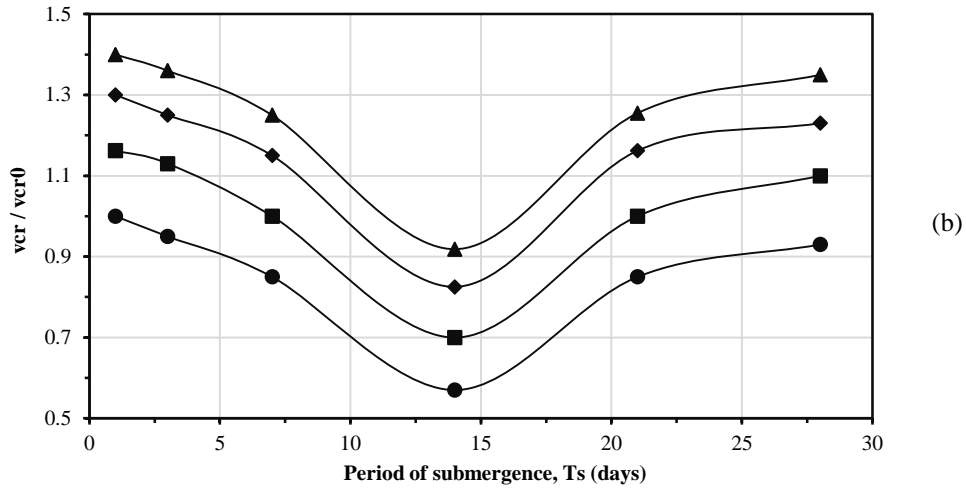
(b)
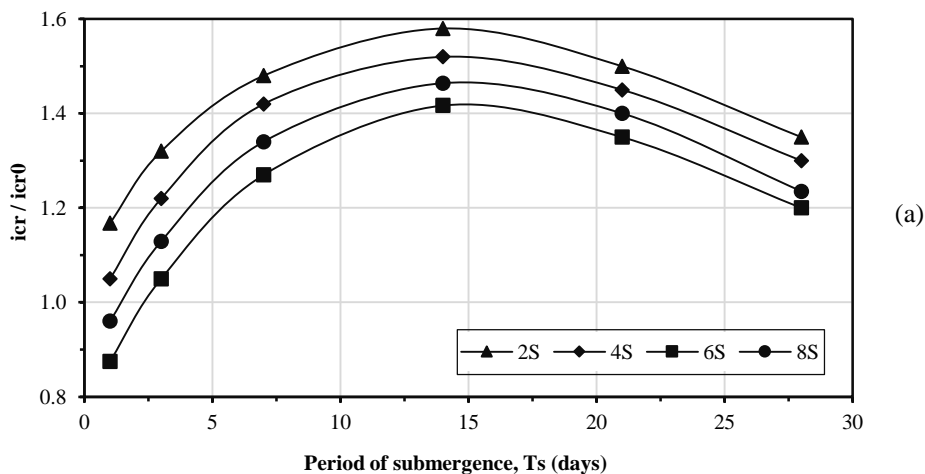
Figure 11. Variation of critical flow parameters with T_s for: (a) hydraulic gradient, and (b) flow velocity

The above observations are justifiable due to the possible two opposing phenomena of chemical decomposition of sand particles with prolonged exposure to saline water and the saltwater adsorption creating cementitious bonds at the particle contacts. Such action is likely to alter the particle sizes which in turn modifies the effective pore sizes. Since the coefficients of hydraulic conductivity alter with the square of pore diameter, a slight variation in the porosity initiated by saline water produced a significant alteration to the coefficients [51, 52].

4.3. Influence of Saline Concentration

The variation of k_1/k^0 with saline concentration is presented in Figure 12. As can be observed, the pattern of variation has been curvilinear. Initially, the value of k_1 increases up to a peak value and decreased thereafter. The peak values have been attained at a saline concentration of $4S$ and the point of contra-flexure was noted at $8S$.
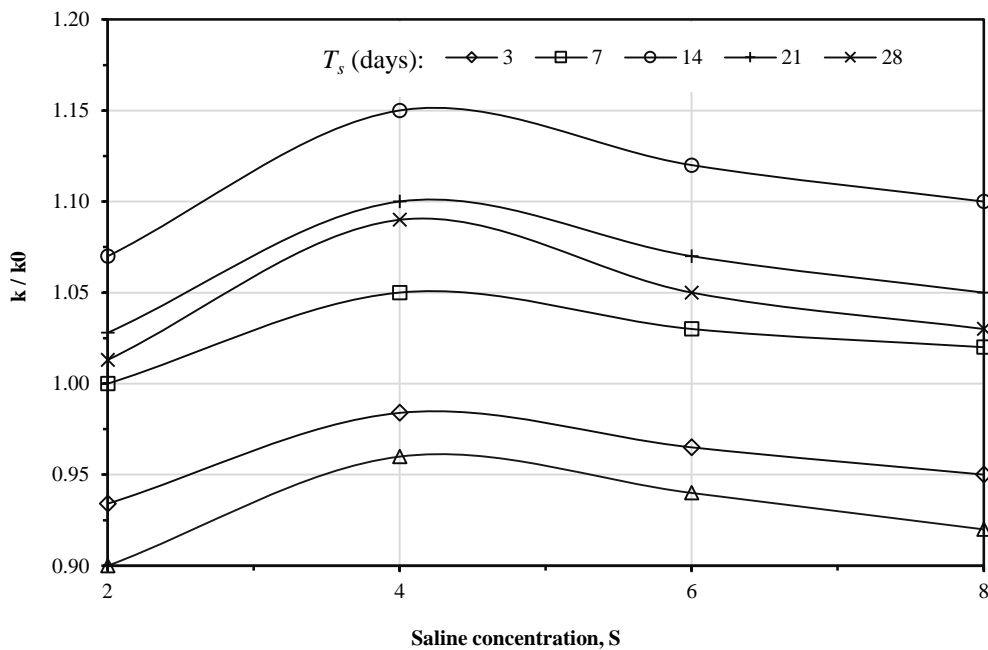

Figure 12. Variation of normalized permeability coefficient (k/k^0) with saline concentration

The variation of k_1/k_1^0 with saline concentration is presented in Figure13-a. As observed, the first coefficient of non-linear hydraulic conductivity decreased linearly with increasing saline concentration, the lines being gradually converging. Figure13-b depicts the variation of k_2/k_2^0 with saline concentration. The pattern of variation is observed to be curvilinear with descending slope. Initially, the values of k_2/k_2^0 was found to increase till a peak was attained at $4.3S$, followed by a gradual reduction.
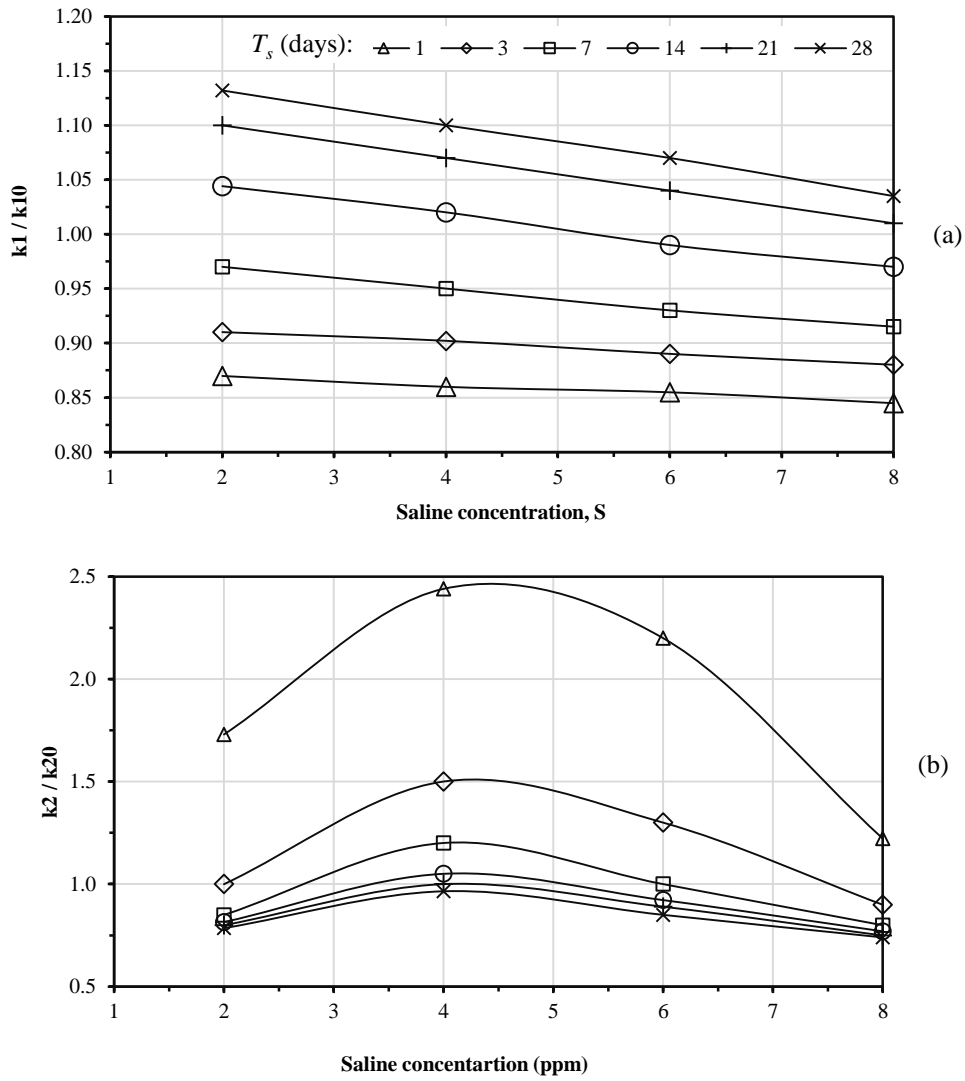
Figure 13. Variation of the coefficients of non-linear hydraulic conductivity with saline concentration for: (a) k₁/k₁⁰, and (b) k₂/k₂⁰

Figure 14-a shows the variation of i_{cr}/i_{cr}^0 with saline concentration, which is observed as curvilinear. With ascending saline concentration, the critical hydraulic conductivity was initially found to decrease till a minimum value was attained at $6S$ and thereafter increased. Figure 14-b studied the variation of normalized critical velocity (v_{cr}/v_{cr}^0) with saline concentration. As observed, v_{cr}/v_{cr}^0 decreases curvilinearly with increasing S with descending slope.
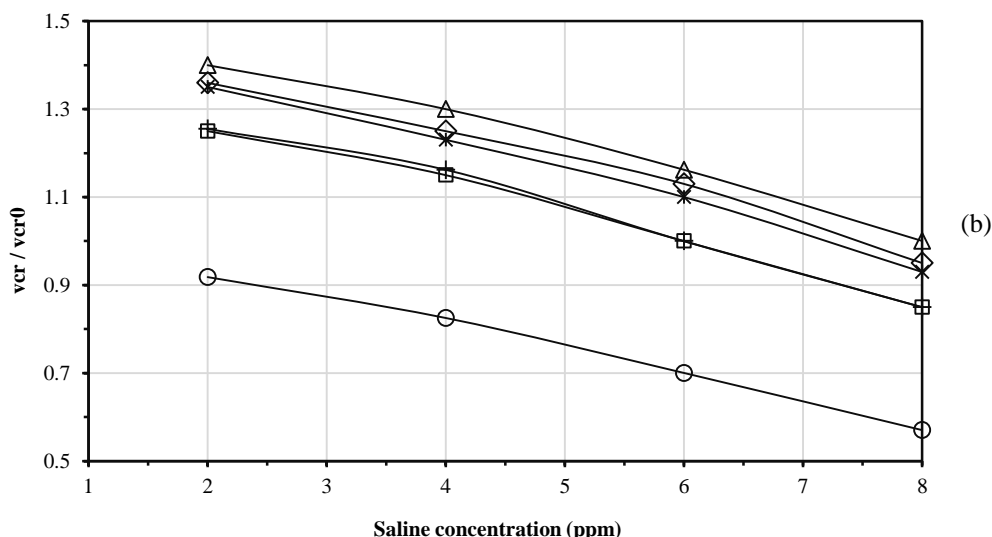
(b)
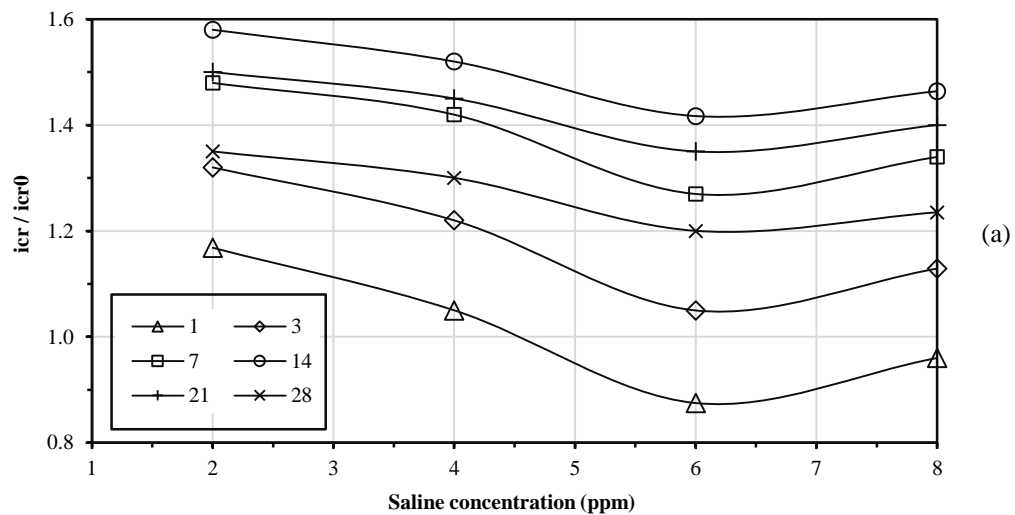
Figure 14. Variation of critical flow parameters with saline concentration for: (a) hydraulic gradient, and (b) flow velocity

The possible reason for the above-mentioned patterns of variation is the complex chemical and electrochemical interaction between the sand particles and the saline solution including cation exchange and anion adsorption, apart from the effects of fluid concentration and stress on the double-layer [53]. The rate of such interactions are likely to alter with the variation of saltwater concentration, due to which the above pattern of variation has been observed.

4.4. Comparison with Past Studies

The current laboratory test data has been compared with a past study by Fatahi et al. [1], as shown in Figure 15. As observed, a similarity in the pattern of variation of the normalized linear hydraulic conductivity (k/k^0) with the period of submergence is noted. However, a significant deviation in the magnitudes has been found. The past study was conducted with kaolin clay at a saline concentration of 24S, whereas, the current study has been performed with fine sand at a saline concentration up to 8S. This is the justified reason for such deviation.
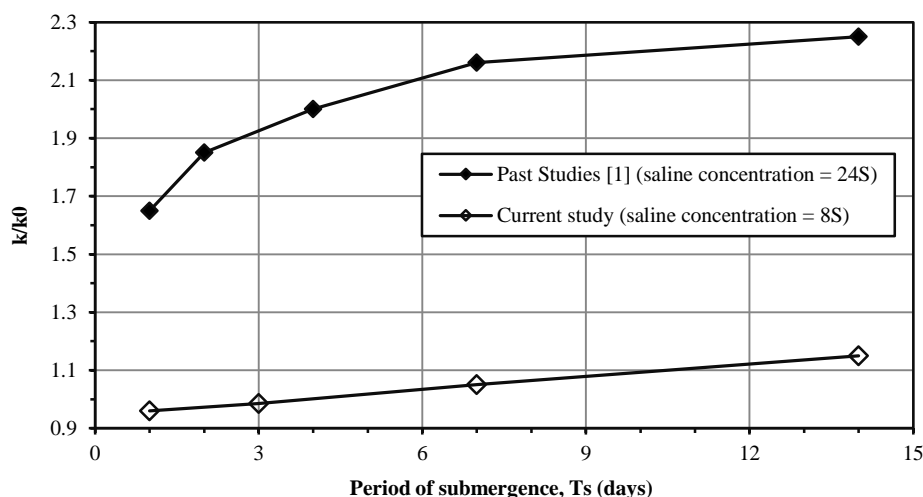

Figure 15. Comparison of current test results with past studies [1]

5. Summary and Conclusions

5.1. Summary

The influence of saltwater intrusion on the flow characteristics through granular soil has been studied in detail through laboratory investigation. The study reveals that a gradual increase in hydraulic gradient initiates a transition of the flow pattern through soil mass from linear to non-linear and vice versa. For linear flow, Darcy's law of permeability yields reasonable values, whereas, in the case of non-linear flow, the applicability of Forchheimer's Equation comes into play. The period of submergence and the saline concentration were found to influence the coefficients of hydraulic conductivity significantly.

5.2. Conclusions

With an increasing period of submergence, the value of the linear coefficient of hydraulic conductivity was found to increase up to a peak value and thereafter decreased curvilinearly. The parameter k_1 was found to increase with T_s following a curvilinear pattern with a descending slope, and the curves progressively converged with increasing saline concentration. The second coefficient of non-linear hydraulic conductivity, k_2 was found to decrease curvilinearly with increasing T_s curvilinearly with ascending slope. The critical hydraulic gradient initially increased curvilinearly with ascending T_s up to a peak and thereafter was found to decrease. With increasing T_s, the critical flow velocity decreased following a curvilinear pattern with a descending slope till a minimum value was attained, and thereafter the parameter was observed to increase.

With increasing saline concentration, the parameter k was observed to increase curvilinearly up to a peak value and then decrease thereafter. The first coefficient of non-linear hydraulic conductivity decreased linearly with increasing saline concentration, with a converging trend. The second coefficient of hydraulic conductivity, on the other hand, was found to be curvilinear with a descending slope, the values being increasing till a peak is attained, followed by reduction. With increasing saline concentration, the parameter i_{cr} was initially found to decrease up to a minimum value and thereafter increase. The variation of critical velocity with saline concentration was curvilinear with a descending slope.

5.3. Novelty and Importance

It is well established that the groundwater flow through porous media may be linear or non-linear, depending upon the induced hydraulic gradient. Therefore, the linear or non-linear coefficients of hydraulic conductivity are the crucial parameters to assess the flow pattern. The coastal environment initiating prolonged exposure to saltwater due to saline water intrusion produces alteration in the values of these coefficients, the extent of which has been studied in the current laboratory-based investigation. The primary importance of the present investigation is the estimation of appropriate values of these coefficients of hydraulic conductivity in the coastal zones, which is useful for conducting seepage analysis and flow patterns for quantifying saltwater intrusion and submarine groundwater discharge. Such a study is beneficial for coastal groundwater modelling and management [6, 54].

5.4. Limitations and Scope of Future Studies

Although an in-depth laboratory-based investigation has been carried out to quantify the pattern of variation of the coefficients of linear and non-linear hydraulic conductivities, the work has few inherent limitations which essentially unfold the scope of future studies, as discussed below:

- The current study is focused on the influence of saltwater intrusion on the hydraulic conductivity of sand. However, the aquifer material may sometimes contain silt or gravel [55], in which case the experimental observations may be different. Extensive investigations are necessary to cover these study aspects.

- While the influence of saltwater exposure on the hydraulic conductivities of aquifer material has been studied, the linear and non-linear groundwater flow patterns in saline water intrusion and submarine groundwater discharge due to such altered flow parameters have yet to be investigated. This would be an interesting area for future study.

6. Declarations

6.1. Author Contributions

Conceptualization, S.B. and G.G.; methodology, S.B.; validation, G.G.; formal analysis, S.B.; investigation, S.B. and G.G.; resources, H.K. and M.K.; data curation, G.G.; writing—original draft preparation, S.B. and G.G.; writing—review and editing, H.K. and M.K.; visualization, H.K. and M.K. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in article.

6.3. Funding

6.4. Acknowledgements

6.5. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Fatahi, B., Khabbaz, S. H., & Basack, S. (2011). Effects of salinity and sand content on liquid limit and hydraulic conductivity. Australian Geomechanics Journal, 46(1), 67–76.

[2] Hussain, M. S., Abd-Elhamid, H. F., Javadi, A. A., & Sherif, M. M. (2019). Management of Seawater Intrusion in Coastal Aquifers: A Review. Water, 11(12), 2467. doi:10.3390/w11122467.

[3] Panthi, J., Pradhanang, S. M., Nolte, A., & Boving, T. B. (2022). Saltwater intrusion into coastal aquifers in the contiguous United States — a systematic review of investigation approaches and monitoring networks. Science of the Total Environment, 836, 155641. doi:10.1016/j.scitotenv.2022.155641

[4] Reilly, T. E., & Goodman, A. S. (1987). Analysis of saltwater upconing beneath a pumping well. Journal of Hydrology, 89(3–4), 169–204. doi:10.1016/0022-1694(87)90179-X.

[5] Bhattacharya, A. K., Basak, S., & Maity, P. (2004). Groundwater extraction in the United Arab Emirates under the constraint of saline water intrusion. Journal of Environmental Hydrology, 12(6), 1-5.

[6] Basack, S., Bhattacharya, A. K., & Maity, P. (2014). A coastal groundwater management model with Indian case study. Proceedings of the Institution of Civil Engineers - Water Management, 167(3), 126–140. doi:10.1680/wama.12.00008.

[7] Goswami, G., Basack, S., Mastorakis, N., Saikia, A., Nilo, B., & Ahmed, N. (2020). Coastal ground water flow and management: A state-of-the-art review. International Journal of Mechanics, 14, 37–48. doi:10.46300/9104.2020.14.5.

[8] Basack, S., Goswami, G., Deka, P., Barman, M. K., & Chishi, K. (2020). Flow Characteristics through Saturated Soil: Experimental Study. Wseas Transactions on Environment and Development, 16, 198–203. doi:10.37394/232015.2020.16.20.

[9] Kiron, B., Basack, S., Goswami, G., & Bida, H. (2021). Hydrological and Environmental Study on Surface Water Characterization in a Locality in North Eastern India. WSEAS Transactions on Environment and Development, 17, 1228–1233. doi:10.37394/232015.2021.17.112.

[10] Dutta, J., Basack, S., Goswami, G., & Kiron, B. (2021). Geomechanical hazards related to river hydraulics and remedial measures: Selected case studies in india. WSEAS Transactions on Fluid Mechanics, 16, 214–221. doi:10.37394/232013.2021.16.20.

[11] Basack, S., Goswami, G., Sonowal, S., & Karakouzian, M. (2021). Influence of Saltwater Submergence on Geohydraulic Properties of Sand: A Laboratory Investigation. Hydrology, 8(4), 181. doi:10.3390/hydrology8040181.

[12] Bobba, A. G. (1993). Mathematical models for saltwater intrusion in coastal aquifers. Water Resources Management, 7(1), 3–37. doi:10.1007/BF00872240.

[13] Haitjema, H., Kuzin, S., Kelson, V., & Abrams, D. (2010). Modeling Flow into Horizontal Wells in a Dupuit-Forchheimer Model. Ground Water, 48(6), 878–883. doi:10.1111/j.1745-6584.2010.00694.x.

[14] Cai, J., Taute, T., & Schneider, M. (2014). Saltwater Upconing Below a Pumping Well in an Inland Aquifer: a Theoretical Modeling Study on Testing Different Scenarios of Deep Saline-Groundwater Pathways. Water, Air, & Soil Pollution, 225(11). doi:10.1007/s11270-014-2203-7.

[15] Kim, D. G., Shin, K. H., & Kim, G. B. (2018). Suitability analysis of saline water intrusion monitoring wells near a waterway based on a numerical model and electric conductivity time series. Geosciences Journal, 22(5), 807–824. doi:10.1007/s12303-018-0001-8.

[16] Akter, S., Ahmed, K. R., Marandi, A., & Schüth, C. (2020). Possible factors for increasing water salinity in an embanked coastal island in the southwest Bengal Delta of Bangladesh. Science of the Total Environment, 713(136668). doi:10.1016/j.scitotenv.2020.136668.

[17] Goswami, R. R., & Clement, T. P. (2007). Laboratory-scale investigation of saltwater intrusion dynamics. Water Resources Research, 43(4). doi:10.1029/2006WR005151.

[18] Basack, S., Bhattacharya, A. K., Sahana, C., & Maity, P. (2010). A study on saline water intrusion and fresh water recharge relevant to coastal environment. WSEAS Transactions on Fluid Mechanics, 5(3), 80–90.

[19] Park, S. U., Kim, J. M., Yum, B. W., & Yeh, G. T. (2012). Three-Dimensional Numerical Simulation of Saltwater Extraction Schemes to Mitigate Seawater Intrusion due to Groundwater Pumping in a Coastal Aquifer System. Journal of Hydrologic Engineering, 17(1), 10–22. doi:10.1061/(asce)he.1943-5584.0000412.

[20] Mehdizadeh, S. S., Vafaie, F., & Abolghasemi, H. (2015). Assessment of sharp-interface approach for saltwater intrusion prediction in an unconfined coastal aquifer exposed to pumping. Environmental Earth Sciences, 73(12), 8345–8355. doi:10.1007/s12665-014-3996-9.

[21] Crestani, E., Camporese, M., & Salandin, P. (2019). An alternative approach to laboratory benchmarking of saltwater intrusion in coastal aquifers. Hydrology and Earth System Sciences Discussions, 1–18. doi:10.5194/hess-2019-127.

[22] Guo, Q., Huang, J., Zhou, Z., & Wang, J. (2019). Experiment and numerical simulation of seawater intrusion under the influences of tidal fluctuation and groundwater exploitation in coastal multilayered aquifers. Geofluids, 2019, 1–17. doi:10.1155/2019/2316271.

[23] Basack, S., Loganathan, M. K., Goswami, G., Baruah, P., & Alam, R. (2022). Review of Risk Assessment and Mitigation Measures of Coastal Aquifers Vulnerable to Saline Water Intrusion. Polish Journal of Environmental Studies, 31(2), 1505–1512. doi:10.15244/pjoes/142382.

[24] Bhattacharya, A. K., & Basack, S. (2009). A Practical Design for Groundwater Extraction in Arid Regions Using Qanats Coupled with Vertical Risers. Electronic Journal of Geotechnical Engineering, 14, 1-8.

[25] Mondal, I., Thakur, S., & Bandyopadhyay, J. (2020). Delineating lateral channel migration and risk zones of Ichamati River, West Bengal, India. Journal of Cleaner Production, 244, 118740. doi:10.1016/j.jclepro.2019.118740.

[26] Lathashri, U. A., & Mahesha, A. (2016). Predictive Simulation of Seawater Intrusion in a Tropical Coastal Aquifer. Journal of Environmental Engineering, 142(12). doi:10.1061/(asce)ee.1943-7870.0001037.

[27] Prasad, K. V. S. R., Sridevi, T., & Sadhuram, Y. (2018). Influence of Dam-Controlled River Discharge and Tides on Salinity Intrusion in the Godavari Estuary, East Coast of India. Journal of Waterway, Port, Coastal, and Ocean Engineering, 144(2), 04017049. doi:10.1061/(asce)ww.1943-5460.0000430.

[28] Meyer, R., Engesgaard, P., & Sonnenborg, T. O. (2019). Origin and Dynamics of Saltwater Intrusion in a Regional Aquifer: Combining 3‑D Saltwater Modeling with Geophysical and Geochemical Data. Water Resources Research, 55(3), 1792–1813. doi:10.1029/2018wr023624.

[29] Hasan, M., Shang, Y., Akhter, G., & Jin, W. (2019). Delineation of contaminated aquifers using integrated geophysical methods in Northeast Punjab, Pakistan. Environmental Monitoring and Assessment, 192(1). doi:10.1007/s10661-019-7941-y.

[30] Michael, H. A., Post, V. E. A., Wilson, A. M., & Werner, A. D. (2017). Science, society, and the coastal groundwater squeeze. Water Resources Research, 53(4), 2610–2617. doi:10.1002/2017wr020851.

[31] Thirumurugan, M., Elango, L., Senthilkumar, M., Sathish, S., & Kalpana, L. (2018). Groundwater Management in Alluvial, Coastal and Hilly Areas. Ground Water Development - Issues and Sustainable Solutions, 109–119. doi:10.1007/978-981-13-1771-2_6.

[32] Vengadesan, M., & Lakshmanan, E. (2019). Management of coastal groundwater resources. Coastal Management, 383-397. Academic Press, Massachusetts, United States. doi:10.1016/B978-0-12-810473-6.00018-2.

[33] Mostafaei-Avandari, M., & Ketabchi, H. (2020). Coastal Groundwater Management by an Uncertainty-Based Parallel Decision Model. Journal of Water Resources Planning and Management, 146(6), 04020036. doi:10.1061/(asce)wr.1943-5452.0001227.

[34] Basack, S., Goswami, G., & Nimbalkar, S. (2021). Analytical and numerical solutions to selected research problems in geomechanics and geohydraulics. WSEAS Transactions on Applied and Theoretical Mechanics, 16, 222–231. doi:10.37394/232011.2021.16.25.

[35] Abu zeid, M. M., & El-Aal, A. K. A. (2017). Effect of salinity of groundwater on the geotechnical properties of some Egyptian clay. Egyptian Journal of Petroleum, 26(3), 643–648. doi:10.1016/j.ejpe.2016.09.003.

[36] Costall, A. R., Harris, B. D., Teo, B., Schaa, R., Wagner, F. M., & Pigois, J. P. (2020). Groundwater Throughflow and Seawater Intrusion in High Quality Coastal Aquifers. Scientific Reports, 10(1). doi:10.1038/s41598-020-66516-6.

[37] Prusty, P., & Farooq, S. H. (2020). Seawater intrusion in the coastal aquifers of India - A review. HydroResearch, 3, 61–74. doi:10.1016/j.hydres.2020.06.001.

[38] Moore, W. S., & Joye, S. B. (2021). Saltwater Intrusion and Submarine Groundwater Discharge: Acceleration of Biogeochemical Reactions in Changing Coastal Aquifers. Frontiers in Earth Science, 9. doi:10.3389/feart.2021.600710.

[39] Crestani, E., Camporese, M., Belluco, E., Bouchedda, A., Gloaguen, E., & Salandin, P. (2022). Large-Scale Physical Modeling of Salt-Water Intrusion. Water, 14(8), 1183. doi:10.3390/w14081183.

[40] Wang, L., Li, Y., Zhao, G., Chen, N., & Xu, Y. (2019). Experimental Investigation of Flow Characteristics in Porous Media at Low Reynolds Numbers (Re→0) under Different Constant Hydraulic Heads. Water, 11(11), 2317. doi:10.3390/w11112317. doi:10.3390/w11112317.

[41] Darcy, H. (1856). Publiquis de la Ville de Dijon. Librainie des Corps Imperiaux des Ponts et Chaussess et des Mines, Paris, France. (In France).

[42] Forchheimer, P. (1901). Water movement through the ground. Z. Ver. German, Ing., 45, 1782-1788. (In German).

[43] United States Department of Agriculture (USDA). (1987). Soil Mechanics Level I-Module 3: USDA Textural Classification Study Guide. Soil Conservation Service, United States Department of Agriculture, Washington, United States. Available online: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044818.pdf (accessed on February 2022).

[44] Swenson, H. A., & Baldwin, H. L. (1965). A primer on water quality. US Department of the Interior, Geological Survey, Reston, United States.

[45] Goswami G. (2019). A laboratory study on the influence of saltwater intrusion on sand relevant to coastal environment. Master Thesis, Department of Civil Engineering, Kaziranga University, Jorhat, Assam, India.

[46] ASTM d854-00. (2000). Standard Test methods for specific gravity of soil solids by water pycnometer. ATM International, Pennsylvania, United States.

[47] ASTM STP523-EB. (1973). Evaluation of Relative Density and its Role in Geotechnical Projects Involving Cohesionless Soils. ATM International, Pennsylvania, United States. doi:10.1520/STP523-EB.

[48] Lunne, T., Knudsen, S., Blaker, Vestgården, T., Powell, J. J. M., Wallace, C. F., Krogh, L., Thomsen, N. V., Yetginer, G., & Ghanekar, R. K. (2019). Methods used to determine maximum and minimum dry unit weights of sand: Is there a need for a new standard? Canadian Geotechnical Journal, 56(4), 536–553. doi:10.1139/cgj-2017-0738.

[49] ASTM D3080/D3080M-11. (2011). Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions. ATM International, Pennsylvania, United States.

[50] ASTM D5084-16a. (2016). Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter. ATM International, Pennsylvania, United States. doi:10.1520/D5084-16A.

[51] Tchistiakov, A. a. (1999). Effect of flow rate and salinity on sandstone permeability. Proceedings of Geothermal Conference Basel, Switzerland, 28-30 Sept 1999, 2, 189–197.

[52] Sparks, D. L. (2003). The Chemistry of Saline and Sodic Soils. Environmental Soil Chemistry (2nd Ed.), Elsevier Science, Amsterdam, Netherlands. 285–300. doi:10.1016/b978-012656446-4/50010-4.

[53] Abderrahmane, B., Naima, B., Tarek, M., & Abdelghani, M. (2021). Influence of Highway Traffic on Contamination of Roadside Soil with Heavy Metals. Civil Engineering Journal, 7(8), 1459–1471. doi:10.28991/cej-2021-03091736

[54] Basack, S., Loganathan, M. K., Goswami, G., & Khabbaz, H. (2022). Saltwater Intrusion into Coastal Aquifers and Associated Risk Management: Critical Review and Research Directives. Journal of Coastal Research, 38(3). doi:10.2112/jcoastres-d-21-00116.1.

[55] Hoque, M. A., Burgess, W. G., & Ahmed, K. M. (2017). Integration of aquifer geology, groundwater flow and arsenic distribution in deltaic aquifers – A unifying concept. Hydrological Processes, 31(11), 2095–2109. doi:10.1002/hyp.11181.