

Severe acid rain simulation using geotechnical experimental tests with mathematical modeling

Aram M. Raheem* and Shno M. Ali^a

Department of Civil Engineering, College of Engineering, University of Kirkuk, Al-Sayada Street, Kirkuk, Iraq

(Received April 18, 2020, Revised April 4, 2022, Accepted April 6, 2022)

Abstract. Severe acid rains can be a major source for geotechnical and environmental problems in any soil depending on the acid type and concentration. Hence, this study investigates the individual severe effects of sulfuric, hydrochloric and nitric acids on the geotechnical properties of real field soil through a series of experimental laboratory tests. The laboratory program consists of experimental tests such as consistency, compaction, unconfined compression, pH determination, electrical conductivity, total dissolved salts, total suspended solids, gypsum and carbonates contents. The experimental tests have been performed on the untreated soil and individual acid treated soil for acid concentrations range of 0% to 20% by weight. In addition, a unique hyperbolic mathematical model has been used to predict significant geotechnical characteristics for acid treated soil. The plastic and liquid limits and optimum moisture content have been increased under the effect of all the used acids whereas the maximum dry density and unconfined stress-strain behavior have been decreased with increasing the acid concentrations. Moreover, the used hyperbolic mathematical model has predicted all the geotechnical characteristics very well with a very high coefficient of determination (R^2) value and lowest root mean square error (RMSE) estimate.

Keywords: acid rain; chemical acids; electrical conductivity; geotechnical experimental tests; hyperbolic model; mathematical modeling; pH value

1. Introduction

The acid rain is an environmental phenomenon that is unexceptionally called transboundary pollution matter where the studies have shown that the sources of the acid rains in the Scandinavian countries were the factories of the United Kingdom, French and Germany (Watmough *et al.* 1999). In addition, countries such as Japan and China were beyond the acid rains in Taiwan and Korea (Lin *et al.* 1999, Yuan *et al.* 2019). Moreover, the black triangle place in the middle of Europe (Czech Republic) is one of the most contaminated places in the world since the coal is used as the source for the power. The sulfur content in the coal is very high where more than 800 thousand tons of SO_2 and 200 thousand tons of NO_x are polluted to the environment in such places that destroyed thousands of hectares of forests (Hruska *et al.* 1996). Up to the end of 1970s, the problems of wide spreading of the acid rain were limited to the North America and European countries. Nevertheless, this problem has been distributed around the world due to the expansion and economic development (Ayers *et al.* 2000). Countries such as Malaysia started having problems with the acid rain where cities, for instance; Kuala Lumpur, Kedah, Johor, and Selangor have a noticeable increase in the acid rain (Bakhshipour *et al.* 2016a). In Malaysia, the

pH values have decreased from the range of (5.0-5.7) to the range of (4.16-4.40) (Ayers *et al.* 2000). In the Middle East, the second gulf war has burnt both oil wells and chemical storages in which thousands tons of sulfur oxides, nitrogen oxides and carbon oxides have missioned into the air and caused acid rains in Iraq. The effects of acid rain on the environment include the marble and calcareous buildings, monuments and statues, ancient sculptures, minerals and iron, paintings of cars and buildings, marshes, streams and lakes. In the places that have alkaline compounds with acid neutralization capacity such as limestone, these compounds work to equalize the acidity of the rains by forming $CaCO_3$ before harm could happen and this phenomenon can be identified in the west of the United States of America and several other places in the Middle East (Miyanaga and Ikeda 1996). However, if the soil is weak in terms of acid neutralization capacity such as granite, the acid rain will influence the water and environmental projects such as northeastern parts of the United States of America. When the water acidity is increased, the released toxic ionic minerals such as Al^{+3} are increased that affect negatively the organisms and it was proved that decreasing the pH from 6 to 5 would increase the concentration of aluminum ions by 100%. It was shown that the numbers of effected lakes by acid rains exceeded 2500 lakes where 1750 of them lost their fishes completely since such lakes were built on granite rock (Colls 2002). The poisonous concern of the aluminum ions can affect the underground waters. The consequences of the acid rains on the plants represent several effects such as weakening the plants due to washing process, affecting bacteria that support nitrogen, decreasing the rate of decomposition of organic materials, increasing

*Corresponding author, Assistant Professor

E-mail: aram_raheem@uokirkuk.edu.iq

^aM.Sc., Instructor

E-mail: shnoma@yahoo.com

the harmful mineral ions of the acid rains, decreasing the plant's resistance for the severe environmental conditions, and decreasing the ability of the plants for the photosynthesis (Alloway and Ayers 1998, Rupali and Sawant 2019).

During the previous three decades from 1980s to 2000s, the Iraqi atmosphere has become different with many contaminations since no environmental security restrictions have been applied (Awadh 2009). In the last decade, the anthropogenic developments in Baghdad were extremely amplified and considered as an issue to release actual contaminant gases to the ecosystem. There are more than ten refineries in Iraq where the highest production unit is the one in Baji with 150000 bpd followed by the one in Basra with 140000 bpd, and the one in Al-Dora with 100000 bpd. After 2003, the Iraqi people have begun using small electrical producers for their households to get the electric power since the overall country strangled from the shutdown of the electrical power after the second gulf war. These household electrical generators, automobiles, many factories of raw materials such as plaster and brick have released various gases continuously to the atmosphere. Thus, the precipitation in Iraq has become more acidic with more unfavorable impacts on the human and ecosystem. In addition, the uncontaminated rain also has an acidic nature due to the presence of carbon dioxide (CO_2) in the air that dissolves in the water and forms carbonic acid (H_2CO_3). The pH for regular rain is about 5.6 and the acid rain has a pH lower than 5.6 (Applin and Jersak 1986). The acid rain decreases the numbers of the agricultural products, type of drinking water, the pH value for the groundwater, the materials and the units of the buildings, and the chemical properties of the soil (Sivapullaiah *et al.* 2009).

In many situations, the top soil layers are covered with water especially when the area is overflowed with precipitation or river (Okunade 2010). In such conditions, the soil will be affected by the pH of the flooded water. It was shown that the calcium salt can enhance both the soil cohesion and angle of internal friction whereas the copper salt decreases the consistency and the strength of the soil (Osuolale *et al.* 2012). It should be noted that methods such as isothermal adsorption experiment (IAE), thermogravimetric analysis, and pycnometer have been used to investigate the type, content, and physical properties of bound water in loess soil (Wang *et al.* 2018). In addition, mercury injection porosimetry (MIP) and constant-head permeability approaches have been applied as new techniques to confirm the validity of Darcy's law in loess soil (Wang *et al.* 2020). Moreover, the X-ray technology has been used to study the structure of loess in the macro-pores level and their effect on the soil permeability (Wang *et al.* 2021).

The increasing amount of soil contamination has represented by the effects of diverse chemicals on the geotechnical characteristics of cohesive soils (Gratchev and Sassa 2009, Bakhshipour *et al.* 2019, Sriraam *et al.* 2019). Acid rain is caused mainly by the air pollution where the major sources of such pollution are nitrogen oxides (NO_x) and sulfur dioxide (SO_2). The presence of the oxides in the acid rains may drop the pH value to the range of 3 to 4.5

that can potentially affect the mechanical performance of the soil (Santamarina *et al.* 2002, Chavali and Reddy 2018). The progress of the dissolution or leaching of ions in the soil depends on the chemical environment that is primarily controlled by pH values. It was described that the leaching of irons reduced several soil properties such as the maximum dry density, compressive strength, and specific gravity whereas it increased the liquid limit, optimum moisture content and plastic limit (Sunil *et al.* 2006, Bakhshipour *et al.* 2016b, Sajjadi *et al.* 2016). Naturally, the soil particles are connected with each other's through the existence of iron oxide. The filtrating of irons from soil causes a weakness in the binders and thus alters the mechanical properties (Sunil *et al.* 2006). It was noticed that the low pH environment can cause substantial variations in the mineral structure of the soil because of the dissolution of both silica and alumina from the soil (Xu *et al.* 2021a). In acidic conditions, the solubility of silica is lower than alumina and this progression most probably would modify several soil properties such as compressibility and shear strength. It was also reported that the acidic liquids initiated the dissolution of calcium carbonates that defeated the bonds of the carbonate among the clay particles leading to a loose structure containing large voids with higher compressibility (Imai *et al.* 2006). Moreover, it was mentioned that the reduction in pH value is associated with the increase of liquid limit, plastic limit and compression since the calcium carbonate is dissolved (Gratchev and Towhata 2016). The second progression is the alteration in the surface electrical characteristics of the colloidal soil fraction. The mechanical conduct of some soils such as kaolinite depends extremely on the pH value that affects the electrical surface potential of colloids in the soil medium (Brandenburg and Lagaly 1988, Chen *et al.* 2000). It was noticed that at the low pH medium, the electrical charge of the edges of kaolinite soil particles turned progressively positive and this activity causes the formation of extra flocculated open fabrics. It was experimentally approved the presence of such fabrics by Wang and Siu 2006. The scanning electron microscopy procedure was used to examine the micro-fabrics for the clay kaolinite particles and it was determined that such fabrics have higher compressibility creating soil structures with extra compression indices because of the edge to face involvement (Dolinar and Trauner 2007).

Another process can be represented by the absorption of ions in the acid rain including NO_3^- , SO_4^{2-} , and CO_3^{2-} in the soil medium. It was indicated that the presence of specific cations in soils exemplified by calcium might change the chemical composition and form the crystalline of CaCO_3 and CaSO_4 and enlarge the unconfined compressive strength during this development. In addition, several other factors such as the amount and soaking time in the acid rain, and cation substitution capacity in the soils can be considered as crucial elements that can alter the interaction between the soil and acid rain (Gratchev and Towhata 2011). The engineering characteristics of the soils might be affected by any variation in the diffuse double layer in the clay extent portion because of the ion exchange followed by the subsequent alteration in the van der Waals



Fig. 1 Satellite picture for the selected site



Fig. 2 Collecting disturbed soil samples in the site

forces between clay particles. As the soil medium becomes acidic, the hydrogen ions involve in the process of exchange with cations for the diffuse double layer for the clay soil particles. Because of the excellent location of the hydrogen ions in the Hofmeister series, they would easily substitute the present exchangeable cations (Gratchev and Towhata 2011). It was proven that clay minerals preserve a strong disintegration and hydrophilicity, increase the cation exchange, lead to loose structure and produce an increase in the size of pores (Xu *et al.* 2021b).

Thus, the thickness of the double layer would change due to the chemistry of the clay colloidal. This change causes an increase in the compressibility and reduction in the shear strength of the soil (Kashir and Yanful 2001). The reviews have shown that the influences of the acid rain on the physical, chemical and engineering characteristics of the soils might be distinctive since the existing minerals for the acid rains and hosted soil are complex and hence their chemical reactions. Consequently, more detailed research works are required for further interpretation to the influence of the acid rain on the soil properties under different environmental conditions. Hence, the principal objective of this study was to investigate the effect of severe acid rain on the geotechnical properties and environmental behavior of real field soil at Kirkuk city. In addition, the specific objectives of this study were as follows:

1. Study the effect of severe acid rain on the geotechnical behavior of the field soil using different chemical acids such as hydrochloric (HCl), sulfuric (H_2SO_4), and nitric (HNO_3) acids.

2. Examine the environmental performance of the filed soil under the effect of simulated severe acid rain.

2. Materials and methods

2.1 Site

In this study, the soil has been selected from the campus of the University of Kirkuk in Kirkuk city in Iraq at the global coordinates of 35.394020, 44.344468 as shown in Fig. 1. The sampling location has been selected since it is the place that the new university campus has been built within the last ten years where insufficient information about the soil condition was available. The site is located in the southern part of Kirkuk city and different areas of the studied location have been exposed to different chemical acids with different rates.

2.2 Drilling and sampling

The soil samples were collected from a depth of 0.5 m to 1 m beneath the ordinary ground level at the campus of the University of Kirkuk that is located in the northern part of Iraq. Manual tools have been used for excavation and collecting undisturbed samples of soil where the upper layer was thrown and the rest of the samples were brought to the laboratory. The process of collecting soil samples in the field is shown in Fig. 2.

2.3 Chemical acids and laboratory experiments

Three different chemical acids represented by hydrochloric (HCl), sulfuric (H_2SO_4), and nitric acids (HNO_3) have been used to treat the soil with different percentages to simulate the severe action of acid rains on

the real field soil. These three different acids have been chosen since they are the main components of acid rain and most of the industrial chemical outputs are one or more of these acid components. The process of preparing any of the used acids started by adding a volume of 0.005 M hydrochloric, sulfuric and nitric acids to a commercially deionized available distilled water. Based on the weight, the prepared acid solution is mixed individually where the added range was from 5% to 20% (as an example and for 5% mixture, the acid solution weight was 5 gm and the soil weight was 100 gm). The selected acid percentages from 5% to 20% can represent a real condition in places with super industrial activities that may increase the acid content to the studied severe rates.

All the laboratory experiments have been performed using ASTM standards. The basic soil properties such as natural water content, specific gravity and particle size distribution have been determined using ASTM D2216-19 (ASTM D2216 2019), ASTM D854-14 (ASTM D 854-14 2014), and ASTM D4822-88 (ASTM D422-88 2019) respectively. In addition, the soils plastic and liquid limits were determined using ASTM D4318-17e1 (ASTM D4318-17 2017) for both untreated and acids treated conditions. The variation of soil dry density versus the moisture content for both untreated and acids treated soils has been measured using ASTM D698-12e2 (ASTM D698 2012). The undrained shear strength for the untreated and acids treated soils was calculated using ASTM D2166 (ASTM D2166 2016). The acidity of the untreated and treated soils was obtained through pH measurement using ASTM D4972-19 (ASTM D4972 2019). The electrical conductivity, total dissolved salt, and total suspended solids were measured based on ASTM D1125-14 (ASTM D1125 2014), ASTM D5907-18 (ASTM D5907-18 2018), and ASTM D5907-18 (ASTM D5907-18 2018) respectively. In these tests, the soil samples are collected from the field, dried and mixed with deionized water to form a sticky wet soil paste. The formed soil paste is allowed to run through a filter over a funnel. The filtered sample is collected in a clean cup and the measurements are recorded using a rinsed probe. The electrical conductivity, total dissolved salt and total suspended solids tests are significant as these tests can give more insights about the severe levels for the acid rains. In addition, these tests can be used as non-destructive measurements for assessing the geotechnical behavior of any soil exposed to severe acid rain. The gypsum content in the untreated and acids treated soils has been determined based on the ASTM C471M-17ae1 (ASTM C471M-17ae1 2017) whereas the carbonate content for both untreated and acids treated soils has been obtained depending on ASTM D4373-14 (ASTM D4373-14 2014). It should be remarked that the carbonate content is calculated by mg/L by multiplying the device reading by a conversion factor of 17.3. For acid-treated soil, dry soil is first treated with varying percentages of acids before carbonate concentration content is measured.

2.4 Analytical model and prediction

For the variety of distinctive geotechnical characteristics

with different acid contents, a nonlinear hyperbolic model has been used. The modeled geotechnical properties are the variety of liquid and plastic limits with acid contents, the variations of maximum dry density and optimum moisture content with the acid contents, and the variety of stress-strain relationships with acid contents. The hyperbolic nonlinear model was used since this model can precisely predict the nonlinear increase or decrease for any dependent variable with an extraordinary degree of reliability. In addition, this model has a physical significance in terms of having a restriction for the maximum predicted variable, which is more suitable for any practical phenomena. In the literature, the proposed hyperbolic model has been used to model the variation of the soil bearing capacity with the used number of geogrids under the foundation (Raheem and Abdulkarem 2016, Lu *et al.* 2016, Oztoprak *et al.* 2018). Previously, the hyperbolic model was utilized to predict the fluid loss versus time of drilling mud prepared from bentonite and tested at high pressure and high temperature (Raheem and Vipulanandan 2020). Furthermore, the hyperbolic model was used to simulate the fluctuation of the shear strength versus electrical resistivity in untreated and polymer-treated soft soil (Raheem and Vipulanandan 2021). The mathematical formulation for the hyperbolic model can be expressed as follows

$$Y = \frac{X}{A+B \cdot X} + \text{Initial Correction} \quad (1)$$

Where A & B are the used model parameters. Y represents the modelled soil property and X represents the acid contents. The initial correction is good for the correct initial modelling.

Both the coefficient of determination represented by R^2 and the root mean square error represented by RMSE are used to check the effectiveness of the proposed model.

$$R^2 = \left(\frac{\sum_i (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_i (X_i - \bar{X})^2} \sqrt{\sum_i (Y_i - \bar{Y})^2}} \right)^2 \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{\sum_i^n (Y_i - X_i)^2}{N}} \quad (3)$$

Where Y_i is the experimental value; X_i is the predicted value from the hyperbolic model; \bar{Y} is the mean of the experimental values; \bar{X} is the mean of the predicted values and N is the number of the data points. The proposed hyperbolic model was shown to be capable of predicting diverse features in various soils.

3. Results and discussion

3.1 Basic physical soil properties

The obtained soil samples were tested in the laboratory and their basic properties are summarized in Table 1. The grain size distribution for the tested soil is shown in Fig. 3. Based on the unified soil classification system, the soil can be classified as lean clay soil (CL soil). The variation of the dry density with the moisture content for the field soil

Table 1 Basic soil properties

Property	Value
Water content	11.3%
Specific gravity	2.72
Liquid limit	40
Plastic limit	28.9

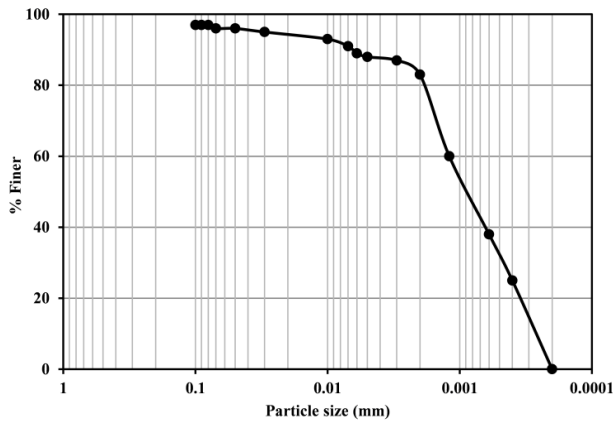


Fig. 3 The grain size distribution for the tested field soil

through the compaction curve can be shown in Fig. 4. The maximum dry density was 16.9 kN/m³ corresponding to an optimum moisture content of 17.7%.

3.2 Plastic and liquid limits results

The variation of the soil plastic limit with the acid concentrations for different types of the used acids can be shown in Fig. 5. The sulfuric acid has the highest effect in increasing the plastic limit for the soil compared with the hydrochloric and nitric acids. As the sulfuric acid concentrations is increased from 0% to 20%, the plastic limit of the soil is increased by 77% whereas the soil plastic limit is increased by 32% as the hydrochloric acid concentrations is increased from 0% to 20%. However, the soil plastic limit is increased by 14% as the nitric acid concentrations is increased from 0% to 20%. Similarly, the variation of the soil liquid limit with the acid concentrations for different types of the used acids can be shown in Fig. 6. Generally, the soil liquid limit is increased with increasing the acid concentrations for all the acid types where the sulfuric acid had the highest impact in increasing the liquid limit. The soil liquid limit is increased by 55% as the sulfuric acid concentrations is increased from 0% to 20%. However, the soil liquid limits are increased by 23% and 10% as both the hydrochloric and nitric acids are increased from 0% to 20% respectively. The increase in both plastic and liquid limits with the increase in acid concentrations is because of ion exchange process and increasing the capability of the particles to absorb more water due to the increase in the particle surface areas. The increase of the clay surface area for acid treated soil has been reported to be twice of the untreated soil as a hydrochloric acid is added to the soil by 1 M (Edama *et al.* 2014). At lower

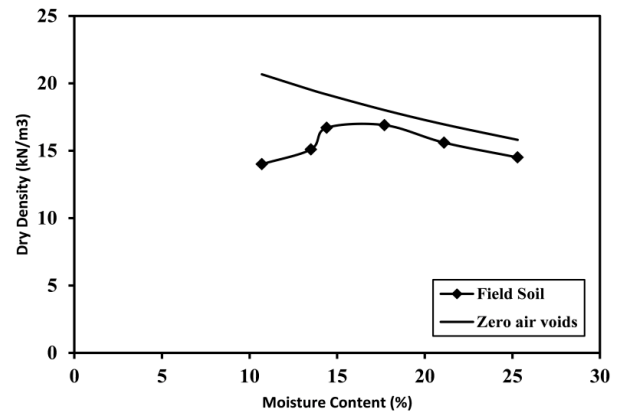


Fig. 4 The compaction curve of the field soil

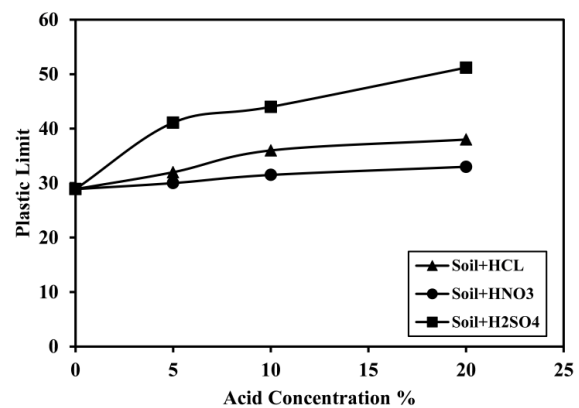


Fig. 5 The variation of the plastic limit with the acid concentrations

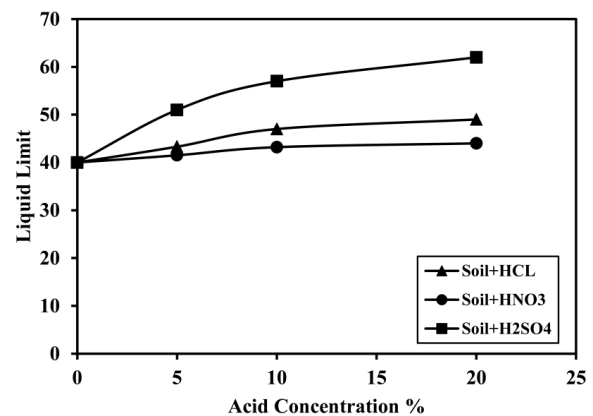
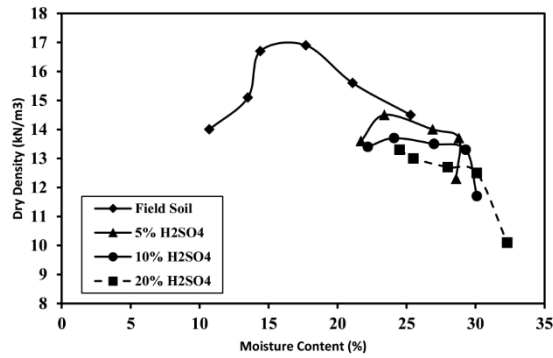
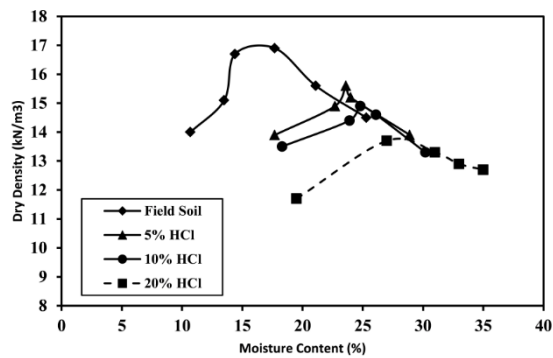


Fig. 6 The variation of the liquid limit with the acid concentrations

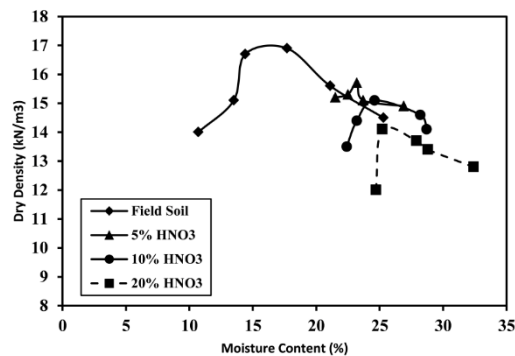
pH values, the liquid and plastic limits are higher because of an ion exchange, which could occur between the hydrogen ion and the aluminum, silicate and iron ions and de-flocculation. Moreover, the acid concentration facilitates the splitting of the soil particles and hence increases the surface area with more water absorption. Increasing both liquid and plastic limits with the presence of different concentrations of acid rains alters the soil location on the classification chart towards a soil with higher plasticity.



(a)



(b)



(c)

Fig. 7 The variation of the dry density with the moisture content for different acid concentrations (a) sulfuric, (b) hydrochloric, and (c) nitric

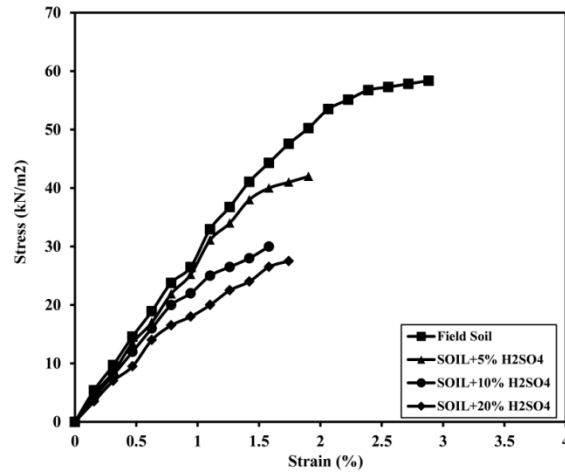
3.3 Dry density-moisture content results

For all the tested acids, the maximum dry density of the field soil is decreased with increasing the acid concentration whereas the optimum moisture content of the field soil is increased with increasing the acid concentration. The variations of dry density with moisture contents under the impact of different sulfuric acid contents are shown in Fig. 7(a). As the sulfuric content is increased from 0% to 20%, the maximum dry density is decreased by 21% and the optimum moisture content is increased by 38%. Similarly, the variations of dry density with moisture contents under the impact of different hydrochloric and nitric acid concentrations are shown in Figs. 7(b) and 7(c) respectively. As the hydrochloric content is increased from 0% to 20%, the maximum dry density is decreased by 19% and the optimum moisture content is increased by 53%. However,

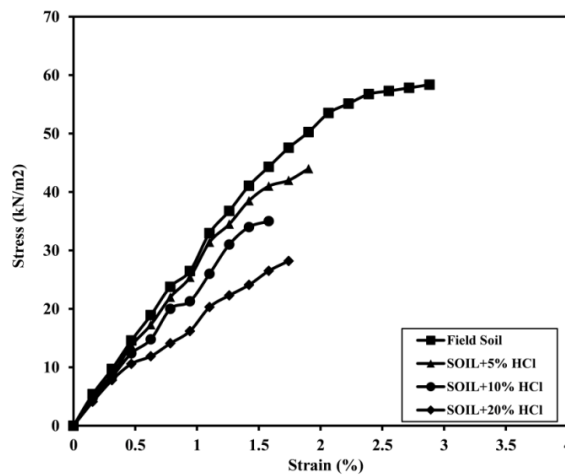
the maximum dry density is decreased by 17% and the optimum moisture content is increased by 42% as the nitric acid concentration is increased from 0% to 20%. The observed decrease in the maximum dry density with the increase in the optimum moisture content is probably attributed to the growth of the texture and the specific surface area due to the interactions between the base and the acid and crushing of soil particles into smaller pieces at higher acid concentrations. Decreasing maximum dry density and increasing optimum moisture content with the presence of different concentrations of acid rains weakens the soil strength and reduces the bearing capacity.

3.4 Unconfined compression results

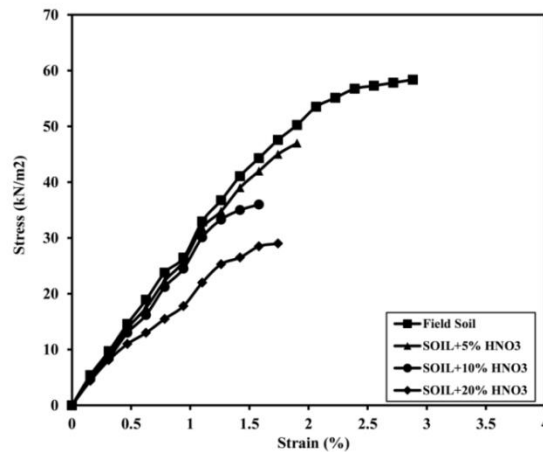
The variation of the unconfined stress-strain relationships for the field soil and treated soil with different



(a)



(b)



(c)

Fig. 8 The variation of the unconfined stress-strain relationships for field soil and treated soil with different acid concentrations (a) sulfuric, (b) hydrochloric, and (c) nitric

sulfuric concentrations can be shown in Fig. 8(a). The soil strength is decreased with increasing the sulfuric contents. As the sulfuric acid concentration is increased from 0% to 20%, the soil strength is decreased by 53%. Similarly, the variation of the unconfined stress-strain relationships for the field soil and treated soil with different hydrochloric

concentrations can be shown in Fig. 8(b). The soil strength is decreased by 47% as the hydrochloric concentration is increased from 0% to 20%. Likewise, the variation of the unconfined stress-strain relationships for the field soil and treated soil with different nitric concentrations can be shown in Fig. 8(c). The soil strength is decreased by 50% as

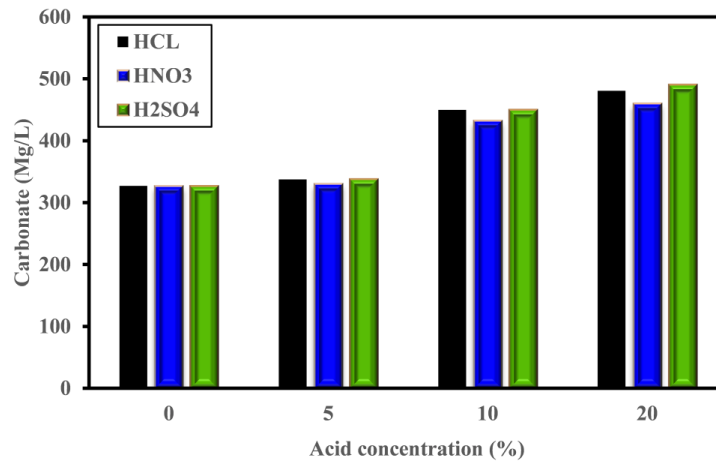


Fig. 9 The variation of the carbonate content for field soil and treated soil with distinctive acids with different concentrations

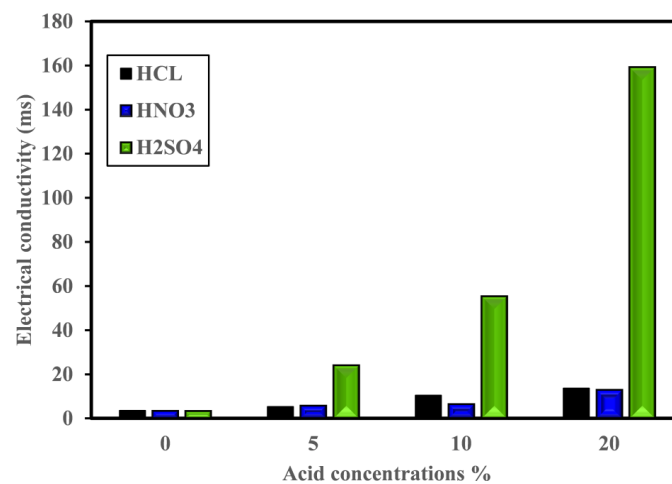


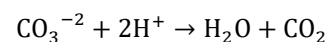
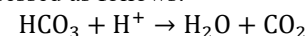
Fig. 10 The variation of the electrical conductivity for field soil and treated soil with distinctive acids with different concentrations

the nitric concentration is increased from 0% to 20%. The reduction in the soil strength with the addition of different acids is mainly due to the drop of the bonding forces among the soil particles because of leaching of soil minerals. The leaching happens since the mixture of the acid content is considered as a strong oxidizer related to the electron contributor characteristics leading to leaching out the iron (III) and aluminum ions into the acidic media. In general, the leachate in soil treated with acids such as hydrochloric acid depends on the ion exchange and dissolution of soil constituents where extraction time is an essential component in the leachate rate. In addition, the acid leachate relies on the nature of the soil and its mineral composition. Both unconfined compressive soil strength and corresponding soil strain are decreased with the presence of acid with different concentrations.

3.5 Carbonate concentration

The variation of carbonate contents with different acid concentration for three used acids including sulfuric,

hydrochloric, and nitric acids is shown in Fig. 9. The initial measured carbonate content in the untreated soil was 327 mg/L. Regardless of the experimental test procedure or the carbonate mineral type and origin, it is clearly noticed that the carbonate content is increased with the increase of the acid concentration. As the acid concentration is increased from 0% to 20%, the carbonate content is increased by 50%, 47% and 41% for sulfuric, hydrochloric and nitric acids respectively. The increase in the carbonate content is mainly because of the chemical reaction between the acids and the soil minerals with the presence of water that would release more carbon dioxide to the medium. It is noticed that the acid solutions initiated the disbanding of calcium carbonates and damaged the carbon bonds among the clay particles. At higher acidic concentrations, the hydrogen ion reacts with the carbonates (CO_3^{-2}) or bicarbonates (CO_3^{-1}) to form carbon dioxide (CO_2) and water. The chemical reaction is expressed as follows:



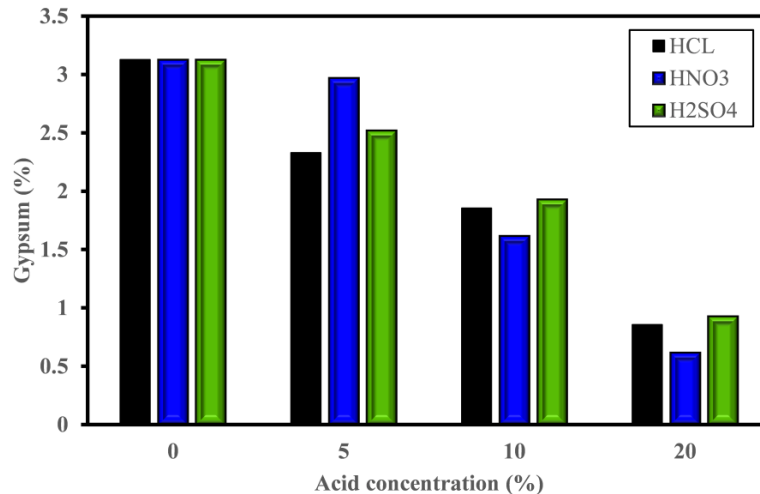


Fig. 11 The variation of the gypsum content for field soil and treated soil with distinctive acids with different concentrations

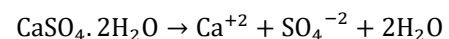
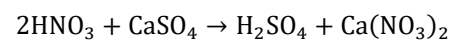
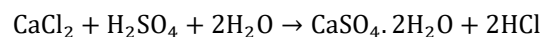
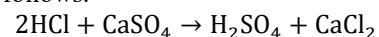
Various acid types with different rates facilitate the process of carbonate conversion from one structure to another to be detectable during carbonate measurement. Thus, the acid treated soil can be used as one of the nondestructive visible methods to monitor carbonate contents in the soil. This type of test may be used in engineering applications to determine the high acid content in clayey soil without destroying the soil, which is a strong indicator for the existence of severe acid rain.

3.6 Electrical conductivity

The variation of the electrical conductivity with different acid concentration for three used acids including sulfuric, hydrochloric, and nitric acids is shown in Fig. 10. The electrical conductivity in the soil is increased with the increase of the acid concentration with different rates. As the acid concentration is increased from 0% to 20%, the electrical conductivity is increased by 4400%, 286% and 267% for sulfuric, hydrochloric and nitric acids respectively. The increase in the electrical conductivity is occurred since more ions are released to the acid treated soil as the acid concentration is increased where the sulfuric acid had the highest potential in increasing the electrical conductivity. Different absorption mechanism for various acids in the soil affects the conductivity values. As more SO_4^{2-} is absorbed, more amount of OH^- is released. The presence of a larger amount of SO_4^{2-} facilitates the process of dissolution of aluminum by forming Al-SO_4 complexes. Thus, greater soluble aluminum is released by H_2SO_4 compared to HNO_3 and HCl and higher conductivity is obtained. It is demonstrated in the literature that surface electrical characteristics of the soil are changed as the soil is treated with acids where these changes alter the diffuse double layer of clay fraction and modify the van der Waals forces between clay particles (Bakhshipour *et al.* 2016b). In addition, the leaching and dissolution of both anions and cations from acid-treated soils are increased. Hence, the electrical conductivity is increased with the increase of the acid concentration at various pH levels.

3.7 Gypsum content

The variation of the gypsum content with different acid concentration for three used acids including sulfuric, hydrochloric, and nitric acids is shown in Fig. 11. The gypsum content in the soil is decreased with the increase of the acid concentration with different rates. As the acid concentration is increased from 0% to 20%, the gypsum content is decreased by 70%, 73% and 80% for sulfuric, hydrochloric and nitric acids respectively. Increasing the ions in the acid treated soil is the primary cause for decreasing the gypsum content where the nitric acid had relatively more potential in decreasing the gypsum content compared to both sulfuric and hydrochloric acids. The chemical reaction is mainly related to calcium sulfate in the soil with the hydrochloric, sulfuric and nitric acids. The chemical reactions for calcium sulfate with different used acids are as follows:



From the chemical reactions, it is identified that the nitric acid is reacting with the calcium sulfate and decreasing the gypsum content by producing sulfuric acid and calcium nitrate. However, the hydrochloric acid reaction produces sulfuric acid and calcium chloride and in the presence of water, the amount of the dihydrated gypsum is reproduced incompatible with the hydrochloric acid. For hydrochloric chemical reaction with soil, calcium sulfate dihydrate is obtained from the interaction between hydrochloric acid and calcium sulfate (first reaction) and the resulted calcium sulfate and water (second reaction). However, sulfuric acid and calcium nitrate is obtained from the chemical reaction between nitric acid and calcium sulfate in the soil (third reaction). Thus, more reduction in

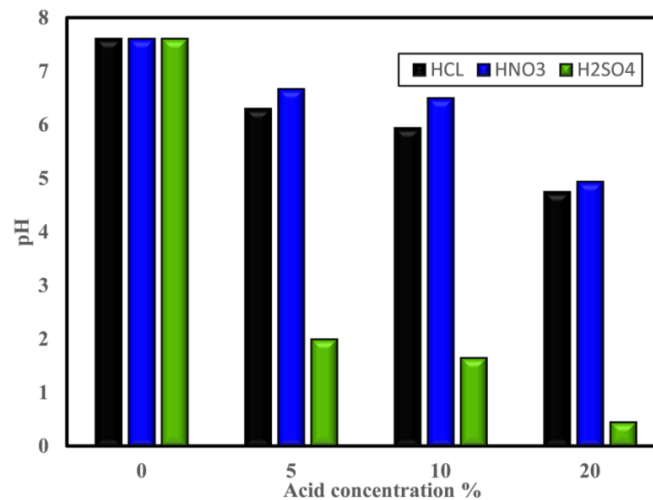


Fig. 12 The variation of the pH value for field soil and treated soil with distinctive acids with different concentrations

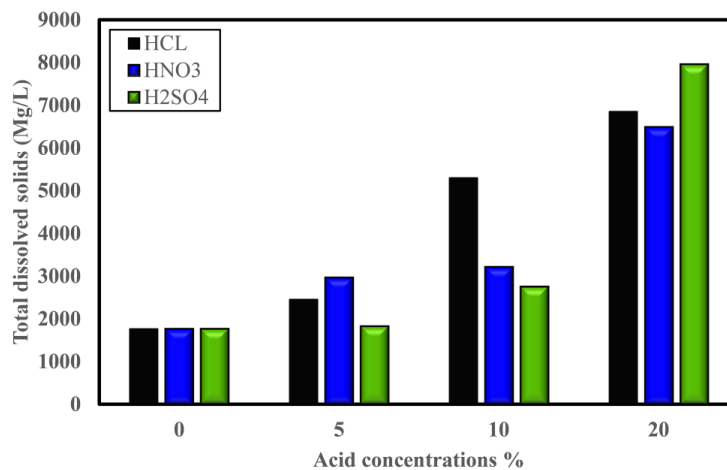


Fig. 13 The variation of the total dissolved salt content for field soil and treated soil with distinctive acids with different concentrations

gypsum content is expected in the case of nitric acid compared to hydrochloric acid. In the case of sulfuric acid reaction with soil, the resulted calcium sulfate dihydrate (fourth reaction) is dissolved into calcium ions, sulfate and water. In addition, the solubility behavior of calcium sulfate in sulfuric acid is controlled by reaction conditions and temperature. Hence, the calcium sulfate (gypsum) is decreased with different rates as distinctive acids react with the soil.

3.8 pH content

The variation of the pH value with different acid concentration for three used acids including sulfuric, hydrochloric, and nitric acids is shown in Fig. 12. The pH value in the soil is decreased with the increase of the acid concentration with different rates. As the acid concentration is increased from 0% to 20%, the pH value is decreased by 94%, 38% and 35% for sulfuric, hydrochloric and nitric acids respectively. Increasing the hydrogen ions in the acid

treated soil is the reason for decreasing the pH value where the sulfuric acid was the strongest acid in decreasing the pH value compared with the other two acids.

3.9 Total dissolved salt

The variations of the total dissolved salt (TDS) content with different acid concentration for three used acids including sulfuric, hydrochloric, and nitric acids are shown in Fig. 13. The released amount of the TDS of the soil itself without any acid addition was 1770 mg/L. The TDS content in the soil is increased with the increase of the acid concentration with different rates. As the acid concentration is increased from 0% to 20%, the TDS content is increased by 350%, 287% and 267% for sulfuric, hydrochloric and nitric acids respectively. The TDS content is increased in acid treated soil because the acids have the tendency to leachate the solid minerals where the sulfuric acid has the most potential in increasing the TDS content. The overall trend of TDS is increased as the acid concentrations are

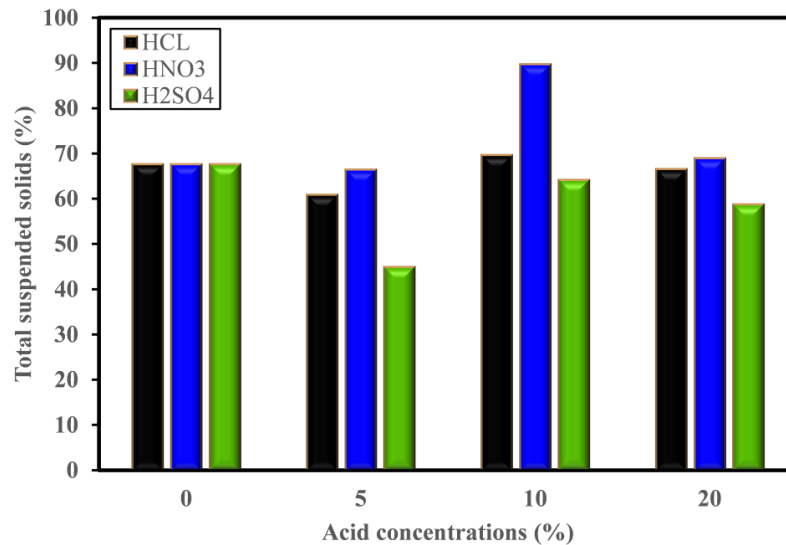


Fig. 14 The variation of the total suspended solids content for field soil and treated soil with distinctive acids with different concentrations

increased, whereas the mechanism of absorbing the acids by the soil is various depending on the type and concentration of acid. For instance, at 10% acid concentration, the hydrochloric acid was the most powerful acid in increasing the TDS whereas the sulfuric acid had the most effect at 20% acid concentration. It is proved that differently charged species anions such as HCO_3^{-1} , SO_4^{-2} , Cl^{-1} , NO_3^{-2} and CO_3^{-2} are one of the causes of increasing total dissolved salt (Corwin and Yemoto 2020). In addition, the dissolution of the anions in the soil is mainly influenced by the constituent solubility at various pH levels (Bakhshipour *et al.* 2016).

3.10 Total suspended solids

The variation of the total suspended solids (TSS) content with different acid concentration for three used acids including sulfuric, hydrochloric, and nitric acids is shown in Fig. 14. The three used acids have different impacts on the TSS content in the acid treated soil. The hydrochloric acid has almost no impact on TSS with a maximum increase of 3% at 10% HCl addition. However, the nitric acid has a fluctuation effect on TSS content with an optimum increase of 33% at 10% HNO_3 addition. In addition, the sulfuric acid has also a fluctuation impact on TSS content with an optimum decrease of 34% at 5% H_2SO_4 addition. The fluctuation effect of the acids on the TSS content is most probably because of different interaction mechanics that could happen between the ions and the distinctive suspended solids. The common diameter of the TSS particles exceeds 2 microns in the size and it can represent inorganic materials, bacteria and algae. All the soil particles including, gravel, sand, silt and clay can be considered as TSS when they are subjected to severe chemical reactions that change their sizes to 0.1 mm-0.001 mm and form suspended soils. The chemical interaction mechanism between different acids and soil particles caused crushing and altering the particles sizes depending on the

acid concentration, chemical composition of the acids and bonding between elements in the crystalline structure. Hence, the fluctuation in the TSS values with acid addition is expected.

3.11 Hyperbolic model prediction

(1) Plastic limit

The plastic limit of a soil is one of the essential soil characteristics that have different uses, such as classifying soils, quantifying toughness index, describing the consistency of soils, predicting soil consolidation properties, and calculating the plasticity index. Such crucial soil characteristic is affected by adding different acid types and concentrations. Thus, the hyperbolic mathematical model has been used to predict the variation of the plastic limit for untreated field soil and acid treated soil with distinctive acids for different concentration of 0% to 20% as shown in Fig. 15. All the used hyperbolic model parameters for plastic limit prediction with R^2 and RMSE are summarized in Table 2. The proposed model predicts all the experimental values very well with a highest R^2 of 0.99 and lowest RMSE of 0.172. In Table 2, the hyperbolic model parameters (A and B) have been optimized by trial and error to get the highest R^2 and minimum RMSE for predicted plastic limit values. In addition, the initial correction in the hyperbolic model has been adjusted to match the initial experimental plastic limit value.

(2) Liquid limit

The second fundamental soil characteristic is the liquid limit that is used as an indicator for soil compressibility. It is observed that the liquid limit is altered by adding different acid types and concentrations. Thus, the hyperbolic mathematical model has been used to predict the variation of the liquid limit for untreated field soil and acid treated soil with distinctive acids for different concentration of 0% to 20% as shown in Fig. 16. All the used hyperbolic model parameters for liquid limit prediction with R^2 and

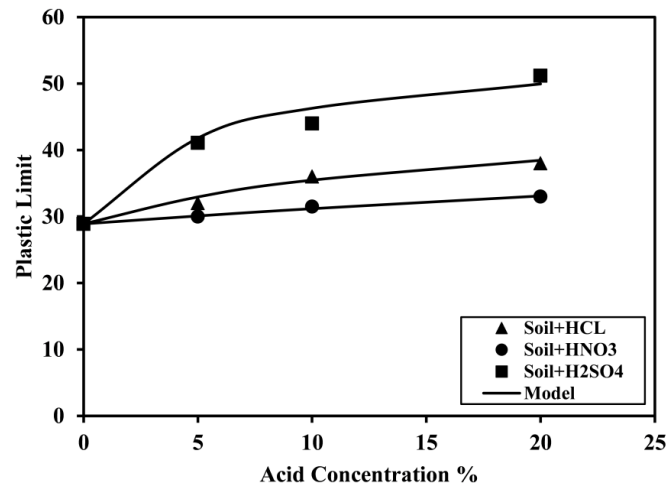


Fig. 15 Hyperbolic Mathematical modeling of plastic limit for untreated and acid treated soil

Table 2 Hyperbolic model parameters used for plastic limit prediction

Acid Type	A	B	R ²	RMSE	Initial Correction
H ₂ SO ₄	0.2	0.0375	0.98	1.350	28.9
HCl	0.95	0.057	0.99	0.589	28.9
HNO ₃	4	0.038	0.99	0.172	28.9

Table 3 Hyperbolic model parameters used for liquid limit prediction

Acid Type	A	B	R ²	RMSE	Initial Correction
H ₂ SO ₄	0.268	0.032	0.99	0.341	40
HCl	1.9	0.014	0.99	1.119	40
HNO ₃	3.0	0.088	0.99	0.328	40

RMSE are summarized in Table 3. The proposed model predicts all the experimental values very well with a highest R² of 0.99 and lowest RMSE of 0.328. In Table 3, the hyperbolic model parameters (A and B) have been optimized by trial and error to get the highest R² and minimum RMSE for predicted liquid limit values. In addition, the initial correction in the hyperbolic model has been adjusted to match the initial experimental liquid limit value.

(3) Maximum dry density

It is known that the maximum dry density of soil is important for field compaction and it was noticed that such density is changed when different acid types and concentrations are added. Henceforth, the hyperbolic mathematical model has been used to predict the variation of the maximum dry density for untreated field soil and acid treated soil with distinctive acids for different concentration of 0% to 20% as shown in Fig. 17. All the used hyperbolic model parameters for maximum dry density prediction with R² and RMSE are summarized in Table 4. The proposed model predicts all the experimental values very well with a highest R² of 0.99 and lowest RMSE of 0.051. In Table 4, the hyperbolic model parameters (A and B) have been

Table 4 Hyperbolic model parameters used for maximum dry density prediction

Acid Type	A	B	R ²	RMSE (kN/m ³)	Initial Correction
H ₂ SO ₄	-0.85	-0.235	0.99	0.051	16.9
HCl	-2	-0.225	0.98	0.239	16.9
HNO ₃	-3.5	-0.19	0.98	0.055	16.9

optimized by trial and error to get the highest R² and minimum RMSE for predicted maximum dry density values. In addition, the initial correction in the hyperbolic model has been adjusted to match the initial experimental maximum dry density value.

(4) Optimum moisture content

The optimum moisture content of a soil is crucial in terms of achieving the required compaction and decreasing the susceptibility of the soil settlement. It was noticed that the optimum moisture content is varied by adding different acid types and concentrations. Consequently, the hyperbolic mathematical model has been used to predict the variation of the optimum moisture content for untreated field soil and acid treated soil with distinctive acids for different concentration of 0% to 20% as shown in Fig. 18. All the used hyperbolic model parameters for optimum moisture content prediction with R² and RMSE are summarized in Table 5. The proposed model predicts all the experimental values very well with a highest R² of 0.99 and lowest RMSE of 0.093. In Table 5, the hyperbolic model parameters (A and B) have been optimized by trial and error to get the highest R² and minimum RMSE for predicted optimum moisture content values. In addition, the initial correction in the hyperbolic model has been adjusted to match the initial experimental optimum moisture content value.

(5) Stress-strain behavior

The soil stress-strain behavior is used to determine several significant parameters such as strength, toughness, elasticity, strain energy, and resilience. Such stress-strain behavior is affected by adding various acid types and

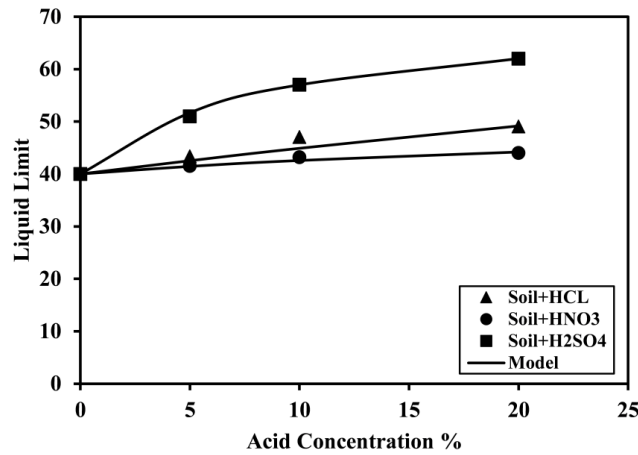


Fig. 16 Hyperbolic Mathematical modeling of liquid limit for untreated and acid treated soil

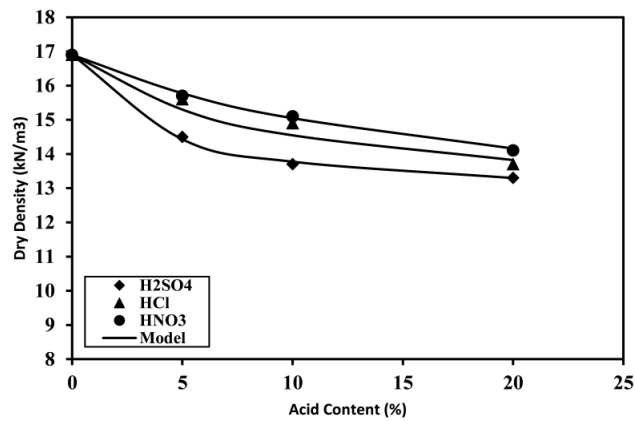


Fig. 17 Hyperbolic Mathematical modeling of maximum dry density for untreated and acid treated soil

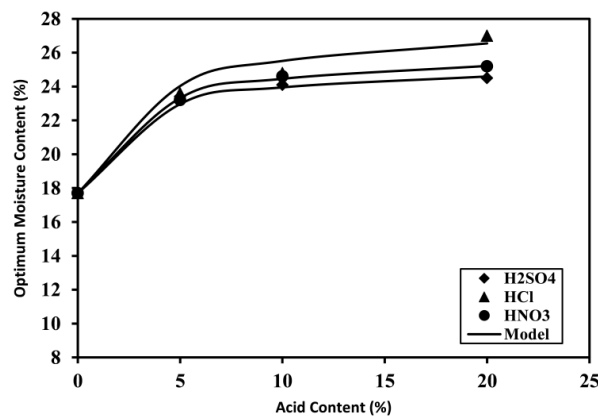
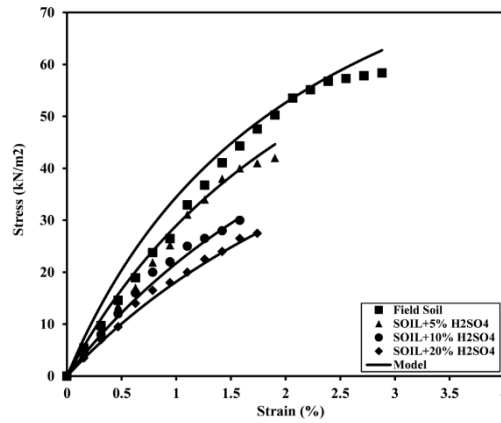


Fig. 18 Hyperbolic Mathematical modeling of optimum moisture content for untreated and acid treated soil

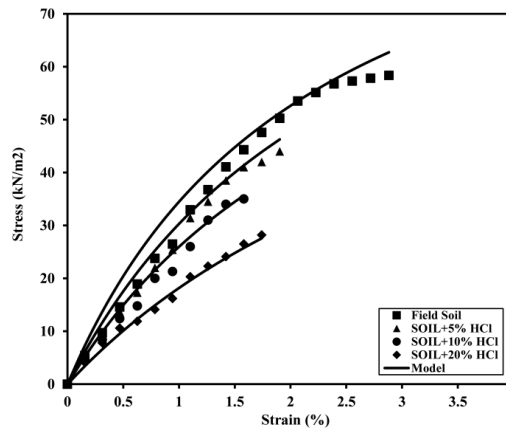
concentrations. Thus, the hyperbolic mathematical model has been used to predict the variation of the unconfined stress-strain behavior for untreated field soil and H₂SO₄ acid treated soil with different concentration of 0% to 20% as shown in Fig. 19(a). All the used hyperbolic model parameters for the stress-strain behavior prediction with R² and RMSE are summarized in Table 6. The proposed model predicts all the experimental values very well with a highest

R² of 0.98 and lowest RMSE of 0.778. In Table 6, the hyperbolic model parameters (A and B) have been optimized by trial and error to get the highest R² and minimum RMSE for predicted stress values of H₂SO₄ acid. In addition, the initial correction in the hyperbolic model has been adjusted to match the initial experimental stress value of H₂SO₄ acid.

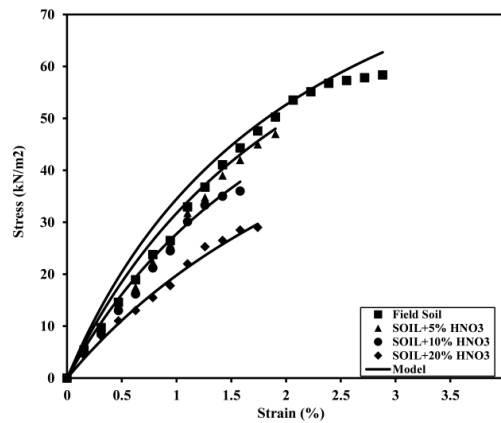
Similarly, the hyperbolic mathematical model has been



(a)



(b)



(c)

Fig. 19 Hyperbolic Mathematical modeling of stress-strain behavior for untreated and acid treated soil (a) H₂SO₄, (b) HCl, and (c) HNO₃.

Table 5 Hyperbolic model parameters used for maximum dry density prediction

Acid Type	A	B	R ²	RMSE	Initial Correction
H ₂ SO ₄	0.3	0.13	0.98	0.235	17.7
HCl	0.3	0.098	0.99	0.472	17.7
HNO ₃	0.3	0.118	0.99	0.093	17.7

used to predict the variation of the unconfined stress-strain behavior for untreated field soil and HCl acid treated soil

with different concentration of 0% to 20% as shown in Fig. 19(b). All the used hyperbolic model parameters for the stress-strain behavior prediction with R² and RMSE are summarized in Table 7. The proposed model predicts all the experimental values very well with a highest R² of 0.99 and lowest RMSE of 0.759. In Table 7, the hyperbolic model parameters (A and B) have been optimized by trial and error to get the highest R² and minimum RMSE for predicted stress values of HCl acid. In addition, the initial correction in the hyperbolic model has been adjusted to match the initial experimental stress value of HCl acid.

Table 6 Hyperbolic model parameters used for H₂SO₄ stress-strain behavior prediction

Acid Concentration (%)	A	B	R ²	RMSE (kN/m ²)	Initial Correction
0	0.02	0.009	0.97	3.375	0
5	0.0255	0.009	0.97	1.821	0
10	0.036	0.010	0.98	0.989	0
20	0.044	0.011	0.98	0.778	0

Table 7 Hyperbolic model parameters used for HCl stress-strain behavior prediction

Acid Concentration (%)	A	B	R ²	RMSE (kN/m ²)	Initial Correction
0	0.02	0.009	0.97	3.375	0
5	0.24	0.009	0.99	2.283	0
10	0.0285	0.01	0.99	1.795	0
20	0.044	0.011	0.99	0.759	0

Table 8 Hyperbolic model parameters used for HNO₃ stress-strain behavior prediction

Acid Concentration (%)	A	B	R ²	RMSE (kN/m ²)	Initial Correction
0	0.02	0.009	0.97	3.375	0
5	0.0225	0.009	0.99	2.817	0
10	0.026	0.01	0.98	1.737	0
20	0.0395	0.011	0.99	0.825	0

In addition, the hyperbolic mathematical model has been used to predict the variation of the unconfined stress-strain behavior for untreated field soil and HNO₃ acid treated soil with different concentration of 0% to 20% as shown in Fig. 19(c). All the used hyperbolic model parameters for the stress-strain behavior prediction with R² and RMSE are summarized in Table 8. The proposed model predicts all the experimental values very well with a highest R² of 0.99 and lowest RMSE of 0.825. In Table 8, the hyperbolic model parameters (A and B) have been optimized by trial and error to get the highest R² and minimum RMSE for predicted stress values of HNO₃ acid. In addition, the initial correction in the hyperbolic model has been adjusted to match the initial experimental stress value of HNO₃ acid.

It should be noted that the proposed model for the nonlinear plastic limit, liquid limit, maximum dry density, and optimum moisture content variations versus acid concentration can be used with a high degree of reliability for any acid values within the range of the study. When the acid concentration reaches an infinity value mathematically, the predicted variable represented by plastic limit, liquid limit, maximum dry density, and optimum moisture content approaches 1/B. It means that the proposed nonlinear hyperbolic model has a limiting value for the maximum predicted variable to be compatible with field and practical limitation and this is the real physical potential for the used

suggested model. In addition, the stress-strain hyperbolic nonlinear model for both untreated and acids treated soils have a similar degree of reliability with the same physical and practical potential.

4. Conclusions

In this study, the impact of severe acid rain on the geotechnical and environmental properties of field soil has been investigated. In which, the severe rain has been represented using three different acids (sulfuric, hydrochloric, and nitric) where such acids have been added individually to the soil with various concentrations from 0% to 20% by weight. In addition, a unique nonlinear hyperbolic model has been used to predict several vital geotechnical characteristics for the acid treated soils. Based on the tested experimental and nonlinear hyperbolic model, the following conclusions can be advanced:

- The sulfuric, hydrochloric, and nitric acids have the potential to increase the plastic and liquid limits of the tested soil where the soil plasticity is increased in the presence of high acid concentrations.
- The sulfuric, hydrochloric, and nitric acids have the tendency to reduce both of the soil strength and bearing capacity as such acids decrease the maximum dry density and increase the optimum moisture content with different rates.
- All the used acids have altered the soil behavior towards a weaker plastic region as the unconfined compressive strength is decreased and the corresponding strain is increased with higher acid contents.
- It can be proved that different nondestructive measurements such as carbonate content, electrical resistivity, gypsum content, and pH values can be used as monitoring evaluation for the different acid concentrations in the soil. These tests can identify the high acid concentration in clayey soil without damaging the soil, which is a significant signal of the presence of severe acid rain.
- It is shown that the proposed nonlinear hyperbolic mathematical model is the best unique model to predict different soil characteristics such as plastic and liquid limits, maximum dry density and optimum moisture content, and unconfined stress-strain behavior of untreated and acid treated soils. In addition, the proposed model has predicted all the experimental data very well with very high R² and low RMSE values. Moreover, the proposed hyperbolic model is capable to be compatible with field and practical limitations.
- The practical application for the combination of such high acid concentration with field soil is relevant for the places with high industrial activities where limited environmental restrictions are appropriate. In these places, different acids with high concentrations are mixed with the rains and the field soils are exposed to such rains with acid contents. The advantage of this work for field engineers is focused on identifying various physical, chemical, geotechnical, and environmental aspects of clayey soils exposed to high concentrations of different acids.

References

- Alloway, B.J. and Ayers, D.C. (1998), "Chemical principle of environmental pollution", *Water Air Soil Pollut.*, **102**, 216-218. <https://doi.org/10.1023/A:1004986209096>.
- Applin, K.R. and Jersak, J.M. (1986), "Effects of airborne particulate matter on the acidity of precipitation in Central Missouri", *Atmos. Environ.*, **20**(5), 965-969. [https://doi.org/10.1016/0004-6981\(86\)90280-5](https://doi.org/10.1016/0004-6981(86)90280-5).
- ASTM C471M-17ae1. (2017), "Standard Test Methods for Chemical Analysis of Gypsum and Gypsum Products (Metric)", *ASTM Int.*, West Conshohocken, PA, USA. <https://doi.org/10.1520/C0471M-17AE01>.
- ASTM D1125-14. (2014), "Standard Test Methods for Electrical Conductivity and Resistivity of Water", *ASTM Int.*, West Conshohocken, PA, USA. <https://doi.org/10.1520/D1125-14>.
- ASTM D2166 / D2166M-16. (2016), "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil", *ASTM Int.*, West Conshohocken, PA, USA. https://doi.org/10.1520/D2166_D2166M-16.
- ASTM D2216-19. (2019), "Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass", *ASTM Int.*, West Conshohocken, PA, USA. <https://doi.org/10.1520/D2216-19>.
- ASTM D4318-17e1. (2017), "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils", *ASTM Int.*, West Conshohocken, PA, USA. <https://doi.org/10.1520/D4318-17E01>.
- ASTM D4373-14. (2014), "Standard Test Method for Rapid Determination of Carbonate Content of Soils", *ASTM Int.*, West Conshohocken, PA, USA. <https://doi.org/10.1520/D4373-14>.
- ASTM D4822-88. (2019), "Standard Guide for Selection of Methods of Particle Size Analysis of Fluvial Sediments (Manual Methods)", *ASTM Int.*, West Conshohocken, PA, USA. <https://doi.org/10.1520/D4822-88R19>.
- ASTM D4972-19. (2019), "Standard Test Methods for pH of Soils", *ASTM Int.*, West Conshohocken, PA, USA. <https://doi.org/10.1520/D4972-19>.
- ASTM D5907-18. (2018), "Standard Test Methods for Filterable Matter (Total Dissolved Solids) and Nonfilterable Matter (Total Suspended Solids) in Water", *ASTM Int.*, West Conshohocken, PA, USA. <https://doi.org/10.1520/D5907-18>.
- ASTM D698-12e2. (2012), "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft³ (600 kN-m/m³))", *ASTM Int.*, West Conshohocken, PA, USA. <https://doi.org/10.1520/D0698-12E02>.
- ASTM D854-14. (2014), "Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer", *ASTM Int.*, West Conshohocken, PA, USA. <https://doi.org/10.1520/D0854-14>.
- Awadh, S.M. (2009), "The Atmospheric Pollution of Baghdad City", *The Proceeding of 3rd scientific conference of College of Science*, University of Baghdad, Iraq, 1727-1740.
- Ayers, G.P., Peng, L.C., Fook, L.S., Kong, C.W., Gillett, R.W. and Manins, P.C. (2000), "Atmospheric concentrations and deposition of oxidised sulfur and nitrogen species at Petaling Jaya, Malaysia, 1993-1998", *Tellus. B.*, **52**(1), 60-73. <https://doi.org/10.3402/tellusb.v52i1.16082>.
- Bakhshipour, Z., Asadi, A., Huat, B.B.K., Sridharan, A. and Kawasaki, S. (2016a), "Effect of acid rain on geotechnical properties of residual soils", *Soils Found.*, **56**(6), 1008-1020. <https://doi.org/10.1016/j.sandf.2016.11.006>.
- Bakhshipour, Z., Asadi, A., Huat, B.B.K. and Sridharan, A. (2016b), "Long-term intruding effects of acid rain on engineering properties of primary and secondary kaolinite clays", *Int. J. Geosynth. Ground Eng.*, **2**(21). <https://doi.org/10.1007/s40891-016-0059-1>.
- Bakhshipour, Z., Asadi, A., Sridharan, A. and Huat, B.B.K. (2019), "Acid rain intrusion effects on the compressibility behaviour of residual soils", *Environ. Geot.*, **6**(7), 460-470. <https://doi.org/10.1680/jenge.15.00081>.
- Brandenburg, U. and Lagaly, G. (1988), "Rheological properties of sodium montmorillonite dispersions", *Appl Clay Sci.*, **3**(3), 263-79. [https://doi.org/10.1016/0169-1317\(88\)90033-6](https://doi.org/10.1016/0169-1317(88)90033-6).
- Chavali, R.V.P. and Reddy, P.H.P. (2018), "Control of phosphoric acid induced volume change in clays using fly ash", *Geomech. Eng.*, **15**(6), 1135-1141. <https://doi.org/10.12989/gae.2018.15.6.1135>.
- Chen, J., Anandarajah, A. and Inyang, H. (2000), "Pore fluid properties and compressibility of kaolinite", *J. Geotech. Geoenviron. Eng.*, **126**(9), 798-807. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2000\)126:9\(798\)](https://doi.org/10.1061/(ASCE)1090-0241(2000)126:9(798)).
- Colls, J. (2002), *Air Pollution*, (2nd Ed.), Spon Press, New York, USA.
- Corwin, D.L. and Yemoto, K. (2020), "Salinity: electrical conductivity and total dissolved solids", *Soil Sci. Soc. Am. J.*, **84**, 1442-1461. <https://doi.org/10.1002/saj2.20154>.
- Dolar, B. and Trauner, L. (2007), "The impact of structure on the undrained shear strength of cohesive soils", *Eng Geol.*, **92**(1-2), 88-96. <https://doi.org/10.1016/j.enggeo.2007.04.003>.
- Edama, N.A., Sulaiman, A., Hamid, K.H.K., Rodhi, M.N.M., Musa, M. and Rahim, S.N.A. (2014), "The effect of hydrochloric acid on the surface area, morphology and physico-chemical properties of Sayong kaolinite clay", *Key Eng. Mater.*, **594-595**, 49-56. <https://doi.org/10.4028/www.scientific.net/KEM.594-595.49>.
- Gratchev, I. and Towhata, I. (2011), "Compressibility of natural soils subjected to long-term acidic contamination", *Environ. Earth Sci.*, **64**(1), 193-200. <https://doi.org/10.1007/s12665-010-0838-2>.
- Gratchev, I. and Towhata, I. (2016), "Compressibility of soils containing kaolinite in acidic environments", *KSCSE J. Civ. Eng.*, **20**(2), 623-630. <https://doi.org/10.1007/s12205-015-0141-6>.
- Gratchev, I.B. and Sassa, K. (2009), "Cyclic behavior of fine-grained soils at different pH values", *J. Geotech. Geoenviron. Eng.*, **135**(2), 271-280. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2009\)135:2\(271\)](https://doi.org/10.1061/(ASCE)1090-0241(2009)135:2(271)).
- Hruska, J., Cerny, J. and Krecek, J. (1996), "The acidification in the Czech part of the black triangle region", *Proceedings of the CRIEPI Int'l seminar on transport and effects of acidic substances*, Tokyo, Japan, Nov. 28-29.
- Imai, G., Komatsu, Y. and Fukue, M. (2006), "Consolidation yield stress of Osaka-Bay pleistocene clay with reference to calcium carbonate contents", *JASTM Int.*, **3**(7), 1-9. <https://doi.org/10.1520/JAI13325>.
- Kashir, M. and Yanful, E.K. (2001), "Hydraulic conductivity of bentonite permeated with acid mine drainage", *Can. Geotech. J.*, **38**(5), 1034-1048. <https://doi.org/10.1139/t01-027>.
- Lin, N.H., Lee, H.M. and Chang, M.B. (1999), "Evaluation of the characteristics of acid precipitation in Taipei, Taiwan using cluster analysis", *Water Air Soil Pollut.*, **113**, 241-260. <https://doi.org/10.1023/A:1005021209478>.
- Lu, X., Qian, Z., Zheng, W. and Yang, W. (2016), "Characterization and uncertainty of uplift load-displacement behaviour of belled piers", *Geomech. Eng.*, **11**(2), 211-234. <https://doi.org/10.12989/gae.2016.11.2.211>.
- Miyayama, Y. and Ikeda, H. (1996), "Acidification of surface water and its prediction on Japan", *Proceedings of the CRIEPI Int'l seminar on transport and effects of acidic substances*, Tokyo, Japan, Nov. 28-29.
- Okunade, E.A. (2010), "Geotechnical Properties of Some Coal Fly Ash Stabilized Southwestern Nigeria Lateritic Soils", *Mod. Appl. Sci.*, **4**(12), 66-73. <https://doi.org/10.5539/mas.v4n12p66>.
- Osuolale, O.M., Falola, O.D. and Ayoola, M.A. (2012), "Effect of pH on geotechnical properties of laterite soil used in highway

- pavement construction”, *Civil Environ. Res.*, **2**(10), 23-28.
- Oztoprak, S., Sargin, S., Uyar, H.K. and Bozbey, I. (2018), “Modeling of pressuremeter tests to characterize the sands”, *Geomech. Eng.*, **14**(6), 509-517. <https://doi.org/10.12989/gae.2018.14.6.509>.
- Raheem, A.M. and Abdulkarem, M.A. (2016), “Experimental testing and analytical modeling of strip footing in reinforced sandy soil with multi-geogrid layers under different loading conditions”, *Am. J. Civ. Eng.*, **4**(1), 1-11. <https://doi.org/10.11648/j.ajce.20160401.11>.
- Rupali, S. and Sawant, V.A. (2019), “1 D contaminant transport through unsaturated stratified media using EFGM”, *Adv. Environ. Res.*, **8**(1), 1-21. <https://doi.org/10.12989/aer.2019.8.1.001>.
- Sajjadi, S., Mirzaei, M., Nasab, A.F., Ghezelje, A., Tadayonfar, G. and Sarkardeh, H. (2016), “Effect of soil physical properties on infiltration rate”, *Geomech. Eng.*, **10**(6), 727-736. <https://doi.org/10.12989/gae.2016.10.6.727>.
- Santamarina, J.C., Klein, K.A., Wang, Y.H. and Prencke, E. (2002), “Specific surface: determination and relevance”, *Can. Geotech. J.*, **39**(1), 233-241. <https://doi.org/10.1139/t01-077>.
- Sivapullaiah, P.V., Guru Prasad, B. and Allam, M.M. (2009), “Modeling sulfuric acid induced swell in carbonate clays using artificial neural networks”, *Geomech. Eng.*, **1**(4), 307-321. <http://dx.doi.org/10.12989/gae.2009.1.4.307>.
- Sriraam, A.S., Raghunandan, M.S., Ti, T.B. and Kodikara, J. (2019), “Effect of palm oil on the basic geotechnical properties of kaolin”, *Geomech. Eng.*, **18**(2), 179-188. <https://doi.org/10.12989/gae.2019.18.2.179>.
- Sunil, B.M., Nayak, S. and Shrihari, S. (2006), “Effect of pH on the geotechnical properties of laterite”, *Eng. Geol.*, **85**(1-2), 197-203. <https://doi.org/10.1016/j.enggeo.2005.09.039>.
- Raheem, A.M. and Vipulanandan, C. (2020), “Characterizing distinctive drilling mud properties using new proposed hyperbolic fluid loss model for high pressure and high temperature conditions”, *J. King Saud Univ. Eng. Sci.*, <https://doi.org/10.1016/j.jksues.2020.10.002>.
- Raheem, A.M. and Vipulanandan, C. (2021), “Characterization of lime and polymer treated ultra-soft clay soils using the modified vane shear and correlating the shear strengths to the electrical resistivity and CIGMAT miniature penetrometer for nondestructive field tests”, *Geotech. Geol. Eng.*, **39**, 3047-3063. <https://doi.org/10.1007/s10706-021-01677-3>.
- Wang, Y.H. and Siu, W.K. (2006), “Structure characteristics and mechanical properties of kaolinite soil I. Surface charges and structural characterizations”, *Can. Geotech. J.*, **43**(6), 587-600. <https://doi.org/10.1139/t06-026>.
- Wang, H., Qian, H., Gao, Y. and Li, Y. (2018), “Classification and physical characteristics of bound water in loess and its main clay minerals”, *Eng. Geol.*, 105394. <https://doi.org/10.1016/j.enggeo.2019.105394>.
- Wang, H., Qian, H. and Gao, Y. (2020), “Non-darcian flow in loess at low hydraulic gradient”, *Eng. Geol.*, **267**, 105483. <https://doi.org/10.1016/j.enggeo.2020.105483>.
- Wang, H., Qian, H. and Gao, Y. (2021), “Characterization of macropore structure of remolded loess and analysis of hydraulic conductivity anisotropy using X-ray computed tomography technology”, *Environ. Earth Sci.*, **80**, 197. <https://doi.org/10.1007/s12665-021-09405-z>.
- Watmough, S.A., Hutchinson, T.C. and Sager, E.P.S. (1999), “The impact of simulated acid rain on soil leachate and xylem chemistry in a Jack pine (*Pinus banksiana* Lamb.) Stand in northern Ontario, Canada”, *Water Air Soil Pollut.*, **111**, 89-108. <https://doi.org/10.1023/A:1005007518586>.
- Xu, P., Zhang, Q., Qian, H., Yang, F. and Zheng, L. (2021) (a), “Investigating the mechanism of pH effect on saturated permeability of remolded loess”, *Eng. Geol.*, **284**, 105978. <https://doi.org/10.1016/j.enggeo.2020.105978>.
- Xu, P., Zhang, Q., Qian, H., Guo, M. and Yang, F. (2021) (b), “Exploring the geochemical mechanism for the saturated permeability change of remolded loess”, *Eng. Geol.*, **284**, 105927. <https://doi.org/10.1016/j.enggeo.2020.105927>.
- Yuan, F., Chen, M. and Huang, H. (2019), “Square CFST columns under cyclic load and acid rain attack: Experiments”, *Steel Compos. Struct.*, **30**(2), 171-183. <https://doi.org/10.12989/scs.2019.30.2.171>.

CC