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## **Geotechnical properties of hydrocarbon-contaminated soils: a comprehensive review** — [Source link](#)

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# Bulletin of Engineering Geology and the Environment

## Geotechnical Properties of Hydrocarbon-Contaminated Soils: A Comprehensive Review

--Manuscript Draft--

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<b>Article Type:</b>	Review Paper
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<b>Abstract:</b>	<p>The geotechnical characteristics of hydrocarbon-contaminated soils have been concentrated heretofore due to the alarming frequency of hydrocarbon contaminations and also their significant consequences. Over the past three decades, numerous research studies have been conducted in order to investigate hydrocarbon-induced changes in geotechnical properties of soils. The present article is aimed at extensively reviewing almost all relevant academic literature to this subject, and, due to various kinds of soils and hydrocarbon compounds, it tries to provide a brief summary of each research study along with its key findings as well. By this review, it was revealed that geotechnical characteristics of soils such as particle size distribution, Atterberg limits, permeability, optimum moisture content, maximum dry density, compression index, coefficient of consolidation, over-consolidation ratio, cohesion, angle of internal friction, unconfined compression strength, shear strength, and so on can be remarkably influenced by hydrocarbon contaminations. However, the amount of these hydrocarbon-induced changes were highly dependent on various factors including soil and hydrocarbon properties, environmental and operation conditions, weathering process, etc. so that, for each specific geotechnical property, various alterations were reported in scientific literature.</p>
<b>Response to Reviewers:</b>	<p>Response to Reviewer #2's comments:</p> <p>First and foremost, the authors profoundly thank Reviewer #2 for assessing the submitted paper to "Bulletin of Engineering Geology and the Environment" and for his/her valuable comments. In general, all of the proposed corrections have been implemented into the manuscript (highlighted in yellow), and their corresponding responses have been also presented as follows:</p> <p>Reviewer #2: The paper shows a well-documented review for the geotechnical properties of hydrocarbon-contaminated soils. Though, the paper is well organized but some suggestions listed below for reference.</p> <p>1. P4L51-52, I suggest to cite the papers by the order of published years from old to new one. Also, delete the parentheses for UNEP. The same for P5L36-39.</p>

Response: With regard to this reviewer's comment ("years from old to new"), it should be stated that the authors used EndNote X8 software for organizing the references along with the specific EndNote style available in the journal's website ([www.springer.com/earth+sciences+and+geography/engineering+geology/journal/10064?detailsPage](http://www.springer.com/earth+sciences+and+geography/engineering+geology/journal/10064?detailsPage)) which determines/implements all the references automatically. However, the reference of UNEP was corrected throughout the manuscript.

2. P5L31-32, why a symbol (a) here?

Response: "Benzo (a) pyrene" was replaced by "benzo[a]pyrene". Benzo[a]pyrene is a polycyclic aromatic hydrocarbon with the formula of C<sub>20</sub>H<sub>12</sub> which is one of the benzopyrenes, formed by a benzene ring fused to pyrene.

3. P6L29-30, delete the term "by the authors" and "Precisely speaking" in L34.

Response: These phrases were omitted.

4. P7L46-47, delete the sentence "Based on the information presented by Chang et al. (2014)" and add the referee (Chang et al. 2014) at the end of the sentence.

Response: Thanks to this reviewer's comment, the mentioned phrase was deleted, and the relevant reference was embedded at the end of the paragraph.

5. P8L7-15, try to simply this long sentence here.

Response: The long sentence was properly outlined.

6. P11L2-3, do not use the term "something along those lines."

Response: The phrase was deleted.

7. P24, please number the equations and add () for the unit (%).

Response: The number and parentheses were added.

8. P26L34-36, delete "see also," and replace (Jia et al. 2010) by (2010).

Response: The mentioned corrections were implemented

9. P27L53-54, delete "see also," and the outer ().

Response: The phrase and parentheses were deleted.

10. P49L2-3, delete (UNEP).

Response: It was deleted.

11. Delete all the referee's parentheses () for Table 2 and Table 5-6, Table 8-9.

Response: As it was previously mentioned, EndNote X8 software with the specific EndNote style for BOEG (which includes parentheses) was used in this article to organize the references. This procedure was also utilized for writing references in all the tables since the authors believed that a similarity between the references in the context and the tables can be more understandable/trackable for readers. However, if Reviewer #2 still insists on it, the authors will do it accordingly.

12. P65, Table 5, I do not understand the meaning for the column Amount 5,10,15.

Response: The main aim of this table was to summarize types and amounts of hydrocarbon contamination used in the relevant literature to provide a brighter view in readers' mind so that they can find in the table that what type/amount of the contaminants were utilized by the researchers so far. Approximately in all research, hydrocarbon contaminants were reported in terms of wt.% of clean soils. For example,

Tuncan and Pamukcu (1992) used different amounts of Philadelphia Crude oil which equal to 5, 10, and 15 wt.% of basic soil (Marine sediments).

13. All the figures should be revised. For example, the legend should be double column (wider) and put inside the figure to spare the space. Also, adjust the position of symbol (a), (b) etc. on the corner but inside of the figure.

Response: According to the reviewer's comment, all the figures were corrected to convey a better and more obvious meanings, especially for the legends and symbols. However, it was somehow difficult for Fig. 10(b).

14. In Figure 11, revise the referee used in legend e.g. 2017(b) not 2017-b.

Response: The format was corrected.

15. Finally, from figures 7-9, the data shows scattered without a visible trend. The effect of hydrocarbon-contaminated soil on geotechnical properties seems complicated. Can the authors give us some guideline how to evaluate.

Response: With reference to Atterberg limits (Fig. 7), it should be stated that the authors studied precisely all the relevant data reported in the literature, and were not able to find a comprehensive trend describing the effects of hydrocarbons on these limits. To elucidate this fact, the authors have approximately accumulated all the data provided in the literature regarding both LL and PI of hydrocarbon-contaminated soils in this figure. As it can be obviously seen in Fig. 7(a), LL of hydrocarbon-contaminated soils were placed within a specific range of percentages; however, all of the determined PI were somehow scattered (Fig. 7(b)) and there was not an expressive trend to present. However, in each particular research, it could be possible for the authors to draw a specific tendency for the limits. Based on DDL theory, most hydrocarbon compounds, as non-polar fluid, are immiscible in water and acting as two separated phases, and won't be able to create bonds with clay particles. Moreover, the thickness of DDL may be affected by various characteristics of pore fluid. The thickness decreases with increase in valency, and also it is significantly influenced by viscosity. When hydrocarbon compounds are added to fine-grained soils, their viscosity may be also affected, thereby altering the thickness of DDL. In general, these factors may result in not expanding diffuse double-layers around clay particles in the presence of hydrocarbon compounds, and soil plasticity has to take place in different amounts of water, compared with clean soil, thereby making an alteration in PL. However, regarding LL in hydrocarbon-contaminated soils, hydrocarbon molecules forming thin viscous layers surrounding clay particles make LL to change.

As for hydraulic conductivity (Fig. 8), the deposition of hydrocarbon compounds into soil pores, as influential elements governing hydraulic conductivity of soils, considerably decreases soil permeability. Of course, it should be stated that this reduction is highly depended on the properties of soil and hydrocarbon, but, in all cases, a negative impact of contamination on hydraulic conductivity of soil can be detected.

With regard to Fig. 9, based on a careful review on the effects of hydrocarbon contamination on consolidation phenomenon in soils, it can be inferred that hydrocarbon-induced changes in consolidation characteristics ( $C_c$  and  $C_v$ ) of soils were highly dependent on types of both soil and hydrocarbon. On one hand, some of these studies stated that compression index ( $C_c$ ) of soil increased with adding oil content, and on the other hand, a few researchers claimed the opposite behaviour, especially for clayey soils. According to the surface energy method, the surface energy at the hydrocarbon-water interface creates a higher surface tension on the considered interface, and results in decreasing water drainage from soil structure. This procedure can reduce the compressibility of clayey hydrocarbon-contaminated soils. All in all, notwithstanding the proposed trend in the figure, as it was also pointed in the manuscript, it should be stated that there is no clear-cut trend demonstrating the straightforward effects of hydrocarbon contamination on consolidation characteristics of soils, and it is highly dependent on both soil and hydrocarbon properties, and should be separately assessed for each particular case.

Response to Reviewer #3's comments:

Above all, the authors would like to deeply thank Reviewer #3 for assessing our submitted article to Bulletin of Engineering Geology and the Environment and for his/her valuable comments. In general, all of the required corrections have been implemented into manuscript, and their corresponding responses have been also presented as follows:

Reviewer #3: This manuscript has reviewed almost all relevant academic literature about hydrocarbon-contaminated soils, and provided a brief summary of research studies based on various kinds of soils and hydrocarbon compounds. The topic is very important and of great significance, and the methodology is sound. Prior to acceptance for publication, the authors should address the following comments:

1. charts and diagrams are not enough detailed in the front of the passage. Although many descriptions are in the article. But they are not visualized.

Response: With reference to this comment of Reviewer #3, it should be initially stated that the procedure used by the authors in this review article was to do a deep and brief review on all relevant literature to the scope of geotechnical properties of hydrocarbon-contaminated soils. To this aim, firstly, the authors struggled to study all articles and to concisely articulate their research aims and limitations, materials and methods, key results and discussion which the results of these attempts shaped the section of 3.1 (Review of literature). As the respected Reviewer #3 completely knows, it is not possible/reasonable/acceptable to visualize all the results of all the studies in this article, so the authors decided to accumulate/justify/conclude a wide range of scattered results in several figures and tables in section of 3.2 (Review summary), and provide a brief discussion over the results (and possible trends). Generally, for each geotechnical property of hydrocarbon-contaminated soils (i.e. materials and methods, soil microstructure and particle size distribution, Atterberg Limits, hydraulic conductivity, compaction behaviour, consolidation characteristics, angle of internal friction and cohesion, unconfined compression strength, maximum shear modulus (G or G<sub>0</sub>), and weathering) reported in the studied literature, section of 3.2 provides a particular subsection including figures and tables showing detailed data. Moreover, the authors believe that, as a review article, the present work had to observe an acceptable balance in the provision of very detailed data in the context and in the figures/tables since it is not possible to provide very detailed information for several articles of 1991-2017 in an article which must have a reasonable number of words, tables, figures and pages. With regard to this comment, it is also beneficial to observe that although the authors have tried to summarize different aspects of each research and to summarize their key outcomes, this review basically have an aim to clarify the previous endeavors and to uncover future capacity of research in the field of geotechnical characteristics of hydrocarbon-contaminated soils. However, it is still needed to refer to each original work and to be benefitted from their research studies profoundly, based on specific and urgent research needs of readers.

2. Reviews are important in this article.but the author should pay attention to telling us that the relationship between the previous results and present results. The author's innovation is what we focus.

Response: Totally speaking, the authors have the same opinion with Reviewer #3 about the academic/research values of comparing results of similar research on common topics chronologically, and we all know that the key prerequisite of this valuable work is to maintain a few basic common items in all research. By the same token, in the first draft of this review, the authors made an attempt to prepare comparisons among specific geotechnical properties of hydrocarbon-contaminated soils over years, but this strategy could not result in an acceptable/engineering report due to this undeniable fact that, in each work, researchers had their specific choices of soil and hydrocarbon type, there was not a particular common soil/contamination to track, and also their experimental circumstances were also different. Therefore, the authors decided to follow a novel method of reviewing the literature including a provision of an outlined summary of each work in chronological order, and then a summary of probable effects of hydrocarbon contamination on each geotechnical properties showing reasonable trends of hydrocarbon influences on these basic/engineering aspects of soil. Notwithstanding the aforementioned explanation, in

all tables of 5-11 and all figures of 7-11, it was tried to present comparisons among all the reported outcomes for some geotechnical properties of hydrocarbon-contaminated soils; however, due to obvious differences between soil/hydrocarbon types, the observed scattered data are somehow reasonable.

3. The author should highlight that the limitation and weakness of the previous studies and the novelty of the current study.

Response: It should be noted that the main aim of the authors was to write an article reviewing/accumulating all the relevant literature to the scheme of hydrocarbon-contaminated soils. However, in comparison with the other review articles regarding broader topics in geotechnical engineering, the used methodology in this review possesses some novel aspects, it does not merely propose novel methods to assess geotechnical properties of hydrocarbon-contaminated soils which could be compared with the previous studies. However, according to the first part of this beneficial Reviewer #3's comment, it is logical to highlight the limitations/weaknesses of the previous studies and provide a better perspective for the future research. As for the limitations/weaknesses projecting the future possibilities of novel topics of research and not to prolong the manuscript more, wherever it is logical/necessary in subsections of 3.2, the authors added some explanations so as to observe Reviewer #3's ideas, and provide general limitations of the available research which ultimately propose novel topics of research for those interested.

4. Page8 , Line24 : What's your reason to raise such a hypothesis? Some details should be told us clearly.

Response: Thanks to this valuable Reviewer #3's comment, these irrelevant sentences were deleted from the manuscript.

5. Page 40, Line12 :What's the detailed benefits that considering the impacts of weathering and aging process?

Response: In this regard, it should be initially stated that the effects of weathering on properties of hydrocarbon-contaminated soils have been concentrated so far by some researchers like Al-Sanad and Ismael (1997) and Nazir (2011) due to this fact that hydrocarbon compounds can be greatly influenced by weathering process as it was reported by the aforementioned studies. More importantly, the hydrocarbon-contaminated soils are usually exposed to serious environmental conditions, and knowing influences of these factors on geotechnical properties of these soils is beneficial. In this connection, Reviewer #3 can take a look at the authors' recently published article in 2018 in "Soil Dynamics and Earthquake Engineering" entitled "Influence of weathering process on small-strain shear modulus ( $G_{max}$ ) of hydrocarbon-contaminated sand" (via <https://doi.org/10.1016/j.soildyn.2018.01.006>) which clearly assessed the effects of weathering on one of the important geotechnical properties of hydrocarbon-contaminated sand. Moreover, the mentioned article along with its brief summary was added to the end of the section of 3.2.10 (highlighted in Yellow).

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<sup>1</sup> Available on [www.springer.com/earth+sciences+and+geography/engineering+geology/journal/10064?detailsPage](http://www.springer.com/earth+sciences+and+geography/engineering+geology/journal/10064?detailsPage)



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these soils is beneficial. In this connection, Reviewer #3 can take a look at the authors' recently published article in 2018 in "Soil Dynamics and Earthquake Engineering" entitled "Influence of weathering process on small-strain shear modulus ( $G_{max}$ ) of hydrocarbon-contaminated sand" (via <https://doi.org/10.1016/j.soildyn.2018.01.006>) which clearly assessed the effects of weathering on one of the important geotechnical properties of hydrocarbon-contaminated sand. Moreover, the mentioned article along with its brief summary was added to the end of the section of 3.2.10 (highlighted in Yellow).

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4 **Geotechnical Properties of Hydrocarbon-**  
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8 **Contaminated Soils: A Comprehensive Review**  
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## Highlights

- Academic literature discussing geotechnical properties of hydrocarbon-contaminated soils were summarised/reviewed.
- Determination methods of hydrocarbon type and content in soils were concisely pointed.
- Microstructures of hydrocarbon-contaminated soils were evaluated.
- Geotechnical properties of hydrocarbon-contaminated soil were singly analysed.

## Abstract

The geotechnical characteristics of hydrocarbon-contaminated soils have been concentrated heretofore due to the alarming frequency of hydrocarbon contaminations and also their significant consequences. Over the past three decades, numerous research studies have been conducted in order to investigate hydrocarbon-induced changes in geotechnical properties of soils. The present article is aimed at extensively reviewing almost all relevant academic literature to this subject, and, due to various kinds of soils and hydrocarbon compounds, it tries to provide a brief summary of each research study along with its key findings as well. By this review, it was revealed that geotechnical characteristics of soils such as particle size distribution, Atterberg limits, permeability, optimum moisture content, maximum dry density, compression index, coefficient of consolidation, over-consolidation ratio, cohesion, angle of internal friction, unconfined compression strength, shear strength, and so on can be remarkably influenced by hydrocarbon contaminations. However, the amount of these hydrocarbon-induced changes were highly dependent on various factors including soil and hydrocarbon properties, environmental and operation conditions, weathering process, etc. so that, for each specific geotechnical property, various alterations were reported in scientific literature.

**Keywords:** Hydrocarbon; Contamination; Geotechnical properties; Soil; Crude oil

## 1. Introduction

Contamination is described as natural and/or artificial presence of adverse substances into our ecosystem with permanent or transient unfavorable effects (Harrison 2006; Howard et al. 1991), and can be classified into major types including air pollution, water pollution, plastic pollution, noise pollution, light pollution, visual pollution, thermal pollution, littering, radioactive contamination, and soil contamination (Harrison 2001; Harrison 2006). Meanwhile, soil contamination, an aspect of land degradation, is one of the most influential issues in the nature, and may happen in different ways in which diverse materials can act as contaminant including hydrocarbons, heavy metals, herbicides, pesticides, etc. (Arman 1969; Calabrese et al. 2005; Fang and Daniels 1997; Kabata-Pendias 2010). Moreover, soil contamination is noticeable with reference to this fact that soil always plays crucial and basic roles in our lives, and its efficacy has been gradually intensified by ever-increasing pace of life in which industrialization is an undeniable necessity (Yong 2000). The seriousness of quantitative and/or qualitative effects on soil originated by the mentioned types of contaminants have been greatly important so that Food and Agriculture Organization of the United Nation (FAO) announced the year of 2015 as the International Year of Soils (IYS 2015) (Nachtergaele 2015). Intensive farming, deforestation activities, contaminated surface water, agro industry, leaching and landfills, oil drilling and mining, waste disposal, and underground storage tank (UST) as well as all of nonstandard and careless activities on and/or beneath ground surface in industrial and urban areas have been proclaimed in the relevant literature as the main elements which undermine physical, chemical, and engineering properties of soils (Calabrese et al. 2005; Nachtergaele 2015; UNEP 2014; Yong 2000). Beside unavoidable changes in soil caused by environmental factors, man-made activities releasing contaminants into our surroundings can be oftentimes associated with agricultural and/or industrial activities in rural and urban areas. As an example, inappropriate disposal of

1 different kinds of domestic, industrial, and nuclear wastes are among these adverse human  
2 actions (Mirsal 2004).  
3

4 In a general view, the seriousness of soil contamination is highly dependent on properties of  
5 soil contaminants which can be grouped into two main kinds including micro- and macro-  
6 pollutants. Macro-pollutants are on many occasions observed in soil structure in large  
7 amounts; however, micro-pollutants frequently occur in small quantities. Acid-rain-induced  
8 deposits and fertilizers can be grouped as macro-pollutants, and micro-pollutants may include  
9 organic and inorganic materials like heavy metals, pesticides, non-pesticides, hydrocarbons,  
10 and so on (Huat et al. 2014; Mirsal 2004). In the other words, soil contaminants can be  
11 generally defined as natural or artificial chemicals which may be originated from  
12 environmental changes or human interference, and have the capabilities to significantly  
13 influence soil properties in various ways (Pascucci 2011). In this regard, the most involved  
14 chemicals are petroleum hydrocarbons, polynuclear aromatic hydrocarbons (such as  
15 naphthalene and benzo[a]pyrene), solvents, pesticides, lead, and other heavy metals (van der  
16 Perk 2006). The frequency of occurrence of these contaminations in soil are associated with  
17 the degree of industrialization and also intensity of pollution incidences (Calabrese et al.  
18 2005; Nachtergaele 2015; Pascucci 2011; UNEP 2014; van der Perk 2006; Yong 2000).  
19 Among the mentioned types of soil contaminants, hydrocarbon-based contaminants are  
20 significant due to several main reasons including increasing demands on petroleum products  
21 in developed and developing countries, beneficial oil market for both private and public  
22 sectors as well as oil spillage during practical activities (oil exploration, extraction, refining,  
23 storage, and transpiration) (Davis et al. 1972; Hoddinott and O'Shay 1994; Stegmann et al.  
24 2001). As an unforgettable fact, it is worth mentioning that hydrocarbon contamination can  
25 take place without human intervention. Tar pits and seeps are the suitable examples of the  
26 naturally happened hydrocarbon contamination. An area may be a petroleum seep where  
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1 natural hydrocarbon compounds escape from the ground to the surface or the atmosphere, and  
2 seep generally occurs above natural petroleum accumulation reservoirs. However, a tar pit, a  
3 particular type of seeps and also named as asphalt pit, is an area where underground bitumen  
4 naturally permeates onto the earth surface and forms a lake of asphalt (Bunger et al. 1979;  
5 Carrigy 1967). In order to provide factual information about the occurrences of hydrocarbon  
6 contaminations and their importance, the largest hydrocarbon contaminations in history, since  
7 1901, have been tabulated and presented in Table 1 (Aigner et al. 2010; Etkin 1999; Whitson  
8 1999).

9 Moreover, as an example highlighting frequency of occurrences of hydrocarbon  
10 contaminations, the volume of different type of hydrocarbon contaminations occurred in the  
11 west coast of United States of America during the last 14 years (2002-2015) which were  
12 precisely measured by Pacific States/British Columbia Oil Spill Task Force has been  
13 provided in Fig. 1 (Pacific States/British Columbia Oil Spill Task Force 2016). Based on the  
14 data, it was clearly obvious that the total volume of hydrocarbons releasing into the area has  
15 been on the rise during the period of the survey. The total volume of hydrocarbon compounds  
16 released into the environment increased from almost 380000 US gallons in 2002 to near  
17 630000 US gallons in 2015. Furthermore, the types of hydrocarbon compounds determined  
18 by Pacific States/British Columbia Oil Spill Task Force were also presented in Fig. 1. It can  
19 be inferred that crude oil and diesel/marine gas oil were the significant types of hydrocarbon-  
20 based spills in this period of time in the west coast. According to the data which were  
21 provided as a partial record of the global situation, it can be concluded that hydrocarbon  
22 contamination has been a serious issue, and specific attentions have been concentrated to  
23 prevent, control, and remediate its consequences.

24 Due to profits of oil market and its practical usage to respond human's industrial and  
25 domestic demands, since 30s, petroleum exploration has been on the rise. In this regard,



1 petroleum geologists and geophysicists have aimed to search over any probable site to find  
2 suitable points for extraction of crude oil and natural gas (Ahmadi et al. 2016; Rosenberger  
3 2015; Secretariat 2010; Secretariat 2012). From the early stages of exploration to the final  
4 steps of consumption, contamination is an unavoidable phenomenon, and hydrocarbon  
5 contaminants can leak into environment. To add to that, hydrocarbon contaminants may  
6 move downward into the groundwater zone under gravity, and besides contaminating soil on  
7 their pathway, they can be horizontally carried by water, thereby reaching soil elsewhere  
8 again with the aid of capillary action (Bossert and Bartha 1984; Duffy et al. 1980; van der  
9 Perk 2006; Yong 2000).

10 Generally, considering all possible sources of hydrocarbon contaminations in soils,  
11 hydrocarbon-induced influences on the nature can be classified as direct and indirect ones.  
12 Oil spills and tar balls are the important examples of the direct types, but global warming as  
13 well as ocean acidification can be named as the indirect ones. Releasing carbon dioxide into  
14 the air as a by-product of burning petroleum products causes global warming and ocean  
15 acidification. However, presence of hydrocarbon compounds into the nature via oil spills and  
16 tar balls can directly influence soil properties (Hoddinott and O'Shay 1994; Stegmann et al.  
17 2001). Chang et al. (2014) reviewed short- and long-term consequences of oil spillage, as a  
18 hydrocarbon contaminant, into our ecosystem from ecological and societal viewpoints, and  
19 proposed an extensive framework to specify oil impacts on our ecosystem (Chang et al.  
20 2014). It can be concluded that location, time, and rate of oil spills can affect the amount,  
21 extent, depth, toxicity, and duration of contamination. Furthermore, this process may be  
22 influenced by any alteration in weather and temperature of the contaminated area, and also  
23 may be intensified or alleviated if local tides and currents take place (Chang et al. 2014).

24 The environmental influences of hydrocarbon contamination on our ecosystem have been  
25 suitably distinguished so far, and several protocols have been established by authorities in

1 order to mitigate their short- and long-term consequences (Durand and Liss 2002; Loehr et al.  
2 2000). Moreover, soil is a vital element in construction industry, and the effects of  
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4 hydrocarbon contaminations on engineering properties of soil should be considered (Das  
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6 2015). Without a doubt, performance of soil as foundations has been a major research topic  
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8 so far in order to evaluate and to improve its efficiency under different conditions. This  
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10 matter has had significant level of importance with respect to this fact that improvements in  
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12 construction projects in both residential and/or industrial zones has been an incremental  
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14 necessity (Bon and Minami 1986). Due to the previously mentioned requisites of construction  
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16 advancement in oil and gas industries, the improvement strategies in these areas on many  
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18 occasions encounter the challenge of dealing with hydrocarbon-contaminated soils. This  
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20 problem has been intensified considering the benefits of oil market as well as domestic and/or  
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22 industrial needs for petroleum products (Ahmadi et al. 2016; Rosenberger 2015; Secretariat  
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24 2010; Secretariat 2012). With the aim of accurately tackling this situation, numerous research  
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26 studies have been carried out so far in order to investigate the effects of hydrocarbon  
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28 contamination on physical, chemical, and geotechnical characteristics of soils. In these  
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30 endeavors, various soil types and different hydrocarbon contaminants have been considered  
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32 by the use of several analytical methods and experimental apparatus. To the best of our  
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34 knowledge, there has not been any comprehensive review article focusing on geotechnical  
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36 properties of hydrocarbon-contaminated soils up to now. The present article aims at  
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38 extensively reviewing almost all relevant research papers to geotechnical behavior of  
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40 hydrocarbon-contaminated soils. In the first place, the present review provides basic  
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42 information about different hydrocarbons which can be found in soil as contaminants. As an  
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44 important prerequisite for the characterization of hydrocarbon-contaminated soils, a brief  
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46 review on analytical methods of determination of hydrocarbon compounds in soils has been  
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48 also presented. Moreover, after the relevant published research articles were precisely studied  
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1 by the authors, a suitable summary of each research work has been briefly stated in this  
2 article, thereby enabling interested readers to concisely evaluate research circumstances and  
3 results with an acceptable level of preciseness. Afterwards, based on the authors' findings in  
4 this review, the remarkable effects of hydrocarbon contaminations on each one of important  
5 geotechnical properties of soils have been separately summarized. Additionally, wherever it  
6 is required and beneficial, comparable articles are provided as further references.  
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## 16 **2. Hydrocarbon-contaminated soils**

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18 According to the importance and necessity of fundamental information about hydrocarbon  
19 compounds and their presence in soil structures in assessing geotechnical behavior of  
20 hydrocarbon-contaminated soils, this section aims at comprehensively reviewing the  
21 published scientific literature which discuss some aspects of hydrocarbon-contaminated soils  
22 including hydrocarbon compounds, microstructures of hydrocarbon-contaminated soils, and  
23 available methods for determination of hydrocarbons in contaminated soils.  
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### 36 *2.1. Hydrocarbons*

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38 Hydrocarbons are organic compounds which are entirely made of carbon and hydrogen  
39 atoms. In the first place, it should be stated that although hydrocarbons have simple chemical  
40 structures by definition, there are a wide variety of hydrocarbon compounds with different  
41 properties which can be generally categorized into two major groups including aliphatic and  
42 aromatic hydrocarbons (Olah and Molnar 2003). Aliphatic compounds (non-aromatics) are  
43 most often flammable, and could be used as fuel such as methane and liquefied natural gas  
44 (LNG). In addition, aliphatic hydrocarbons as cyclic compounds may be saturated or  
45 unsaturated with single- or multi-bond structures, respectively, and are totally divided into  
46 three different types including alkanes, alkenes, and cycloalkanes. Alkanes (paraffin) are  
47 hydrocarbon structures which purely consist of carbon and hydrogen atoms in tree-like  
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1 configurations with single carbon-carbon bonds ( $C_{2n}H_{2n+2}$ ) like Methane, Ethane, Propane,  
2 Butane, etc. However, unsaturated hydrocarbons having at least one carbon-carbon double  
3 bond are recognized as alkenes or olefins ( $C_{2n}H_{2n}$ ) such as ethylene, ethane, ethanol, and so  
4 on. Furthermore, monocyclic saturated hydrocarbons with chemical structures having only  
5 single side carbon rings are known as cycloalkanes (e.g. cyclopropane, cyclopentane,  
6 cyclohexane, etc.) (Gale 2013). On the other hand, aromatic hydrocarbons (arenes) are  
7 chemical compounds with the strongest type of covalent chemical bonds (sigma bonds)  
8 among carbon atoms shaping a circle. Having a high ratio of carbon-hydrogen in structure,  
9 showing considerable capacity to be subjected to electrophilic substitution reactions, and  
10 enduring significant amount of nucleophilic aromatic substitutions are the most general  
11 characteristics of aromatic hydrocarbons. Monoaromatic (MAHs) and polycyclic aromatic  
12 hydrocarbons (PAHs) are the main categories of aromatic hydrocarbons which consist of only  
13 one benzene ring and two or more benzene rings, respectively. Benzene, toluene,  
14 ethylbenzene, and xylenes (BTEX) are the most seen monoaromatic compounds in petroleum  
15 hydrocarbons, and the simple samples of polycyclic-aromatic hydrocarbons are tetracene,  
16 anthracene, and phenanthrene (Bjørseth 1983). A flowchart which briefly describes different  
17 kinds of hydrocarbons along with their subsets and well-known examples has been provided  
18 by the authors in Fig. 2.

19 In hydrocarbon-contaminated areas, various types of hydrocarbon products with particular  
20 commercial/technical names can be found so that each one may contain some of the above  
21 mentioned kinds of hydrocarbon compounds. In general, the most observed types of  
22 hydrocarbon-based products in soils have been crude oil, bitumen, gasoline, motor oil, engine  
23 oil, diesels, etc. (Harrison 2001) which can be found in Table 2 as well. Meanwhile, it should  
24 be noted that crude oil and natural gas mainly consist of aliphatic compounds in compared  
25 with gasoline which is mainly made of aromatic hydrocarbons. Moreover, bitumen is formed

1 by four major compounds including naphthene aromatics, polar aromatics, asphaltenes, and  
2 some saturated hydrocarbons. Motor oil (or engine oil) is mainly derived from crude oil along  
3 with other particular non-petroleum-based compounds as additives for the purpose of  
4 providing adequate viscosity for being used as lubricant in internal combustion engines.  
5 Furthermore, diesels can be found in three different forms in soils such as petroleum diesel,  
6 synthetic diesel, and biodiesel. Petroleum diesel as the most common form of diesel fuel is  
7 derived from crude oil by use of fractional distillation at atmospheric pressure. However,  
8 synthetic diesel is prepared by use of various raw carbonaceous materials such as biomass  
9 (biomass-to-liquid (BTL)), biogas and natural gas (gas-to-liquid (GTL)), and coal (coal-to-  
10 liquid (CTL)). To add to that, biodiesel or fatty-acid methyl ester (FAME) is produced by  
11 herbal oils or animal fats (biolipids) under transesterification process with methanol (Archer  
12 and Wall 2012).

## 31 *2.2. Microstructural characterization of hydrocarbon-contaminated soils*

32 According to the literature (Berger et al. 2002; Izdebska-Muchaa et al. 2011; Khamehchiyan  
33 et al. 2007), hydrocarbon compounds have the ability to make serious changes in particle  
34 interactions, grain size characteristics, and fabric of fine-grained soils. In this regard, it  
35 should be stated that hydrocarbon-induced alterations can be obviously observed in  
36 morphologies and geometrical specifications of fine-grained soils, thereby making several  
37 changes in their engineering behaviors. As a matter of fact, macroscale behavior of both soil  
38 types can be associated with microscale conditions of their structures which are controlled by  
39 particle conditions and their interactions. Therefore, it can be greatly beneficial to consider  
40 hydrocarbon-induced changes in microstructure of both fine- and coarse-grained soils with  
41 the intent of clearly understanding and analyzing geotechnical behavior of hydrocarbon-  
42 contaminated soils.

1 In the case of fine-grained soils, hydrocarbon-induced changes in microscale characteristics  
2 of soil can be associated with various factors such as double layer theory, physicochemical  
3 effects, soil fabric and microstructure conditions (Izdebska-Mucha and Trzciński 2008;  
4 Izdebska-Muchaa et al. 2011; Quigley and Fernandez 1991). Firstly, it should be noted here  
5 that hydrocarbon compounds can affect porosity of fine-grained soils so that the number and  
6 total area of micropores greatly decrease, but conditions of macropores remain approximately  
7 unchanged. However, the degree of changes is greatly depended on hydrocarbon and soil  
8 properties, and has been different from case to case. Precisely, several parameters defining  
9 morphometric characteristics of pores may be used to describe hydrocarbon-induced changes  
10 in porosity of fine-grained soils including area, perimeter, and diameter of pores. However,  
11 due to a variety of hydrocarbon compounds which may be present in fine-grained soils, such  
12 quantitative morphometric studies should be conducted for each case, and then analyze  
13 accordingly. Moreover, some of geometric parameters of soil pores may be altered by  
14 hydrocarbon contaminants such as shape, anisotropy, and degree of orientation. These  
15 geometric and morphometric characteristics should be accurately studied to analyze the  
16 hydrocarbon-induced changes in microstructure of fine-grained soils (Izdebska-Muchaa et al.  
17 2011). As previously explained, due to influential effects of soil and hydrocarbon properties  
18 on physicochemical and structural properties of hydrocarbon-contaminated soils, it should be  
19 proposed that the evaluation of soil microstructure must be separately conducted for each  
20 particular case. In general, based on the relevant literature (Acar and Olivieri 1989;  
21 Fernandez and Quigley 1991; Izdebska-Mucha and Trzciński 2008; Izdebska-Muchaa et al.  
22 2011; Khamehchiyan et al. 2007; Quigley and Fernandez 1991), it can be stated that  
23 hydrocarbon compounds coating surfaces of clay particles in fine-grained soils can alter  
24 hydrophilic nature of clean clay grains to hydrophobic manner. In addition, hydrocarbons can  
25 create considerable amount of adhesion in inter-particle states of fine-grained soils, and also

1 they can reduce electromagnetic repulsive forces between particles. More importantly,  
2 dispersed state of particles in clean fine-grained soils can be altered into a flocculated  
3 structure due to presence of hydrocarbon compounds in soil skeleton. According to  
4 (Izdebska-Mucha and Trzciński 2008), hydrocarbons can bring about drastic changes in the  
5 fabric of fine-grained soils so that much more isometric pores with bigger size are clearly  
6 observable in contaminated soils in comparison with clean one. However, it may be generally  
7 stated based on filtration studies conducted by Quigley and Fernandez (1991) and  
8 Anandarajah (2003) on the permeability of contaminated soils by organic fluid that  
9 hydrocarbon contaminants can reduce the amount of porosity of fine-grained soils so that its  
10 pore number and total pore perimeter are considerably lower than clean soil (Anandarajah  
11 2003; Quigley and Fernandez 1991). All in all, it is worth mentioning that the induced  
12 alterations in specifications of clay surface caused by non-polar hydrocarbon compounds  
13 with lower dielectric constant may be responsible for disintegrating microaggregates of soil  
14 which forms weakened microstructures for fine-grained soils.

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34 In Fig. 3, SEM images of a natural hydrocarbon-contaminated fine-grained soil collected  
35 from a contaminated area in a fuel transportation center covered by many underground fuel  
36 tanks in northeastern of Poland have been presented (Izdebska-Mucha and Trzciński 2008).  
37 All the specimens of both clean and diesel oil contaminated clayey soil were collected from a  
38 2 meter depth beneath the ground surface. Based on a precise inspection on the provided  
39 SEM images (Fig. 3), obvious changes made by hydrocarbon compounds (diesel oil) in  
40 microstructure of the natural clayey soil can be found. A flocculated fabric along with more  
41 Edge-to-Face (EF) contacts among particles as well as the disintegrated aggregates can be  
42 seen in diesel oil contaminated sample (Fig. 3 (b and d)) in compared with clean one (Fig. 3  
43 (a and c)). Moreover, it can be inferred from the images that hydrocarbon compounds could  
44 change aggregated matrix of clean clayey soil into a loose structure so that a strongly packed  
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1 aggregates and microaggregates in clean sample has altered into a disintegrated loosely  
2 structure. More importantly, in the contaminated structure, Edge-to-Face (EF) contacts are  
3 predominant when compared with clean samples in which the majority of contacts is Face-to-  
4 Face (FF) and Edge-to-Edge (EE).  
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9 In the case of coarse-grained soils, microstructural characterization of hydrocarbon-induced  
10 changes may be more straightforward in comparison with fine-grained soils due to this fact  
11 that physical interactions among particles are dominant in this kind of soil. In general, adding  
12 a particular amount of a hydrocarbon into a coarse-grained soil can create hydrocarbon-  
13 coated particles and fill micro- and macropores of soil. The thickness of the coated layer of  
14 hydrocarbon around each particle can affect its surface roughness (friction) and also create  
15 hydrocarbon-induced cohesion among particles. It seems that, in lower contents of  
16 hydrocarbon, the coated layer can bring about influential amount of cohesion into inter-  
17 particle conditions while its amount is not as much as the required amount to eliminate  
18 friction among particles. However, by adding further hydrocarbons, it can be possible to  
19 completely cover roughness of particles, and consequently omit frictional behavior of soil.  
20 Moreover, it seem that more and more increasing content of hydrocarbon into coarse-grained  
21 soils can effectively decompose interaction relationships among particles, and finally the  
22 majority of soil grains will lose their contacts with neighboring grains. More importantly, it  
23 should be noticed here that this classification of hydrocarbon-induced changes in behavior of  
24 coarse-grained soil is deeply dependent on structural properties of soil and also hydrocarbon  
25 characteristics.  
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### 53 *2.3. Determination of hydrocarbons in contaminated soils*

54 Above all, an accurate determination of amount and type of hydrocarbon compounds in  
55 contaminated soils is a fundamental factor to assess rate of damage and to clarify procedures  
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1 which should be employed to remediate contaminated areas (Brown et al. 1975; McGill and  
2 Rowell 1980; Mirsal 2004). Moreover, a precise determination of hydrocarbon compounds in  
3 contaminated soil is hugely depended on using a careful soil sampling procedure and also an  
4 efficient analytical method (Loehr and Higgins 1965). Due to importance of primary analyses  
5 of hydrocarbon-contaminated soils in assessing the induced changes in soil properties and  
6 also in proposing an efficient protocol to eliminate damages, in this section, a brief summary  
7 of the available methods for determining hydrocarbon compounds in contaminated soils have  
8 been presented herein.  
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Variety of methods for determining amount/type of existing hydrocarbons in soil structure  
have been frequently employed in the literature (Okparanma and Mouazen 2013a). These  
means have not been comprehensively authenticated as a result of this fact that a great variety  
of hydrocarbon materials with various chemical compositions and properties have the  
possibility of contaminating soils, and each one requires particular methods to be used. More  
importantly, it should be stated here that, on one hand, it is essential to determine total  
amount of hydrocarbon compounds in a specific hydrocarbon-contaminated soils, and on the  
other hand, it may be required to precisely ascertain the amount of particular hydrocarbon  
compound in the considered area. All in all, this section is aimed at briefly reviewing the  
available methods of characterizing content of hydrocarbon compounds in hydrocarbon-  
contaminated soils.

In total, two technical terms usually used to describe hydrocarbon-based compounds in soil  
are petroleum hydrocarbons (PHC) and total petroleum hydrocarbons (TPH) (Archer and  
Wall 2012). PHC points to an absolute and precise amount of the whole hydrocarbon  
compounds available in soil which is difficult to be accurately measured. However, the  
measurable amount of hydrocarbons in contaminated soil is usually defined as total  
petroleum hydrocarbons (TPH). Several methods have been utilized by researchers so far in

1 order to accurately determine TPH in hydrocarbon-contaminated soil. However, these  
2 methods are not precise enough by reason of “weathering” and “analytical/extraction  
3 limitations” (Okparanma and Mouazen 2013a). Firstly, hydrocarbon compounds in soil may  
4 be gradually altered as a result of various phenomena such as sorption into soil structure,  
5 chemical reaction by existing substances in soil, volatilization into air, microbial degradation,  
6 and also dissolution in water (Sadler and Connell 2003). Consequently, these weathering  
7 procedures can alter hydrocarbon compounds of soil in terms of both chemical compositions  
8 and physical volume. Hence, characterization of hydrocarbons existing in soil may be a  
9 problematic and challenging task owing to the probable weathering-induced alterations.  
10 Secondly, all proposed methods have their own particular limitations in analytical and  
11 extraction procedures so that each one detects some particular parts of existing hydrocarbons  
12 in contaminated soil. On this subject, it may be beneficial to state that various subsets have  
13 been defined in the literature for hydrocarbon compounds found in soils such as polycyclic  
14 aromatic hydrocarbon (PAH) (Fabbri et al. 2013; Hosseini et al. 2012; Shang et al. 2014),  
15 Volatile Petroleum Hydrocarbons (VPH) (Chang et al. 2010; Elazhari-Ali et al. 2013; Yang  
16 et al. 1995), Extractable Petroleum Hydrocarbons (EPH) (Seeley et al. 2007; Summons et al.  
17 1988), Gasoline Range Organic (GRO) (Suatoni et al. 1975), Diesel Range Organic (DRO)  
18 (Fanchi and Christiansen 2016), etc.

19 Heretofore, various methods have been proposed in literature in order to characterize TPH in  
20 hydrocarbon-contaminated soils. Based on their functionalities and performances, these  
21 methods can be classified into in situ (field) and laboratory methods. In the first place, field-  
22 based methods can be generally categorized into common and special methods (Table 3)  
23 (Whittaker et al. 1995). Common (non-specific) methods are those means by which the  
24 contaminated sites can be fairly assessed, and all types of TPH, saturated and aromatic  
25 hydrocarbons in sediments, can be determined. More importantly, common methods have the

1 required capabilities to analyze hydrocarbon compounds existing in soil and also their  
2 weathering-induced changes. The most applicable non-specific methods are Gas  
3 Chromatography with Flame Ionization (GC-FID) (Snape et al. 2005), Gas Chromatography  
4 with Photo-ionization Detection (GC-PID) (Nölscher et al. 2012), Gravimetric Determination  
5 (Villalobos et al. 2008), Infrared Spectrophotometry (IR) (Aske et al. 2001), Turbidimetry  
6  
7 Ultraviolet and Fluorescence Spectroscopy (Lakowicz 1999), Thin-layer Chromatography  
8  
9 (TLC) (Sherma 2006), High Performance Liquid Chromatography (HPLC) (Engelhardt  
10  
11 2012), Size-exclusion Chromatography (Mori and Barth 2013), Supercritical Fluid  
12  
13 Chromatography (SFC) (Taylor 2008), Total Organic Carbon (Schumacher 2002), Isotope  
14  
15 Ratio Mass Spectrometry (Muccio and Jackson 2009), and Fiber Optic IR Sensor (Harrington  
16  
17 2003). Moreover, some advanced and modified methods (special methods) with a  
18  
19 considerable preciseness in both selectivity and sensitivity have been hitherto proposed to  
20  
21 determine hydrocarbon compounds in soil. The most prominent examples of these specific  
22  
23 methods are Nuclear Magnetic Resonance (NMR) (Andrew 2009), Isotope Dilution Mass  
24  
25 Spectrometry (IDMS) (Heumann 1992), Gas Chromatography Mass Spectrometry (GC-MS),  
26  
27 Electrospray Ionization Mass Spectrometry (ESI-MS) (Molnárné Guricza and Schrader  
28  
29 2015), and High Performance Liquid Chromatography Mass Spectrometry (HPLC-MS)  
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31 (Galceran and Moyano 1994). However, there are some laboratory-based techniques to assess  
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33 TPH in soils including General Gravimetry (Villalobos et al. 2008), Infrared (IR)  
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35 Spectroscopy (Oomens et al. 2003), Gas Chromatography Flame Ionization Detection (GC-  
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37 FID), and Gas Chromatography Mass Spectrometry (GC-MS) (Kopka 2006). In addition, it is  
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39 worth noting that GC-MS and GC-FID can be used in both field and laboratory.  
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53 In a general sense, the available lab-oriented and in situ methods determining TPH in soil  
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55 (Table 3) can be compared and contrasted in terms of important criteria including  
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57 preciseness, safety, time, cost, and so on. For a long time, some particular methods have been  
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1 frequently utilized to investigate TPH and PAH in hydrocarbon-contaminated soils including  
2 lab-based gas chromatography (GC-FID and GC-MS), General Gravimetry, Immunoassay  
3 (IMA) (Wei et al. 2009), and spectroscopic methods (infrared (IR), Raman, and  
4 fluorescence). However, these methods have been always accompanied with a few  
5 disadvantages such as sampling resolution, lack of preciseness, and high costs. Hence, with  
6 the aim of achieving rapid, user-friendly, more accurate and economical methods with fewer  
7 occupational hazards, several new techniques have been recently developed by researchers to  
8 provide much reliable information about hydrocarbon-contaminated soil. In this connection,  
9 field Portable Gas Chromatography Mass Spectrometry (GC-MS) (Haas et al. 2002) as well  
10 as visible and Near-Infrared (vis-NIR) spectroscopy (Okparanma and Mouazen 2013b) can  
11 be mentioned.  
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27 As the subsets of electromagnetic spectroscopy, fluorescence spectroscopic methods  
28 (ultraviolet-induced fluorescence, Rapid Optical Screening Tool, and laser induced  
29 fluorescence) are in situ methods detecting PAHs and some other aromatic rings in  
30 hydrocarbon-contaminated soil (Aldstadt et al. 2002). Ultraviolet-induced fluorescence  
31 (UVIF) can be used with cone penetrometer test (CPT) to provide in situ continuous analyses  
32 of contaminated soil, and can detect TPH, petroleum fuels, oils, and PAHs.  
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### 44 **3. Geotechnical properties of hydrocarbon-contaminated soils**

45 In this section, firstly, the authors make an effort to briefly review some research articles with  
46 significant and key results about various aspects of geotechnical properties of hydrocarbon-  
47 contaminated soils. To this aim, it is tried to concisely pinpoint to the main elements of their  
48 research with the intent of forming a general picture of their frameworks, limitations, and  
49 outcomes. More importantly, the findings published in these relevant literature regarding  
50 geotechnical characteristics of hydrocarbon-contaminated soils have been accurately  
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1 summarized and then presented in several subsections. It should be also added that the  
2 authors have made their best to provide an acceptable level of comparisons with other  
3 relevant literature, wherever if required and beneficial, so as to shape a clear view in the  
4 readers' minds.  
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### 10 11 *3.1. Review of literature*

12 From 1986 to 1994, several research studies were conducted to examine various geotechnical  
13 properties of hydrocarbon-contaminated soils (Budhu et al. 1991; Cook et al. 1992; Evgin  
14 and Das 1992; Foreman and Daniel 1986; Meegoda 1992; Meegoda and Rajapakse 1993;  
15 Meegoda and Ratnaweera 1994; Puri et al. 1994; Tuncan and Pamukcu 1992; Uppot and  
16 Stephenson 1989). In their studies, particular characteristics of geotechnical behavior of  
17 hydrocarbon-contaminated soils were concentrated such as hydraulic conductivity (Budhu et  
18 al. 1991; Cook et al. 1992; Meegoda and Rajapakse 1993; Puri et al. 1994; Tuncan and  
19 Pamukcu 1992), consolidation (Meegoda and Rajapakse 1993; Tuncan and Pamukcu 1992),  
20 and shear strength (Cook et al. 1992; Evgin and Das 1992).  
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36 However, the first comprehensive research in this field, based on the authors' view, was  
37 performed by Al-Sanad et al. in 1995. They carried out several experimental geotechnical  
38 tests on soil samples collected from an area in Kuwait which had been contaminated by a  
39 series of explosions and destruction of oil wells and storage tanks as well as occurrences of  
40 vast oil lakes at the end of the Gulf War (Al-Awadhi et al. 1992; Al-Sanad et al. 1995). To  
41 simulate the conditions of contamination, the researchers mixed Jahra sand, a typical surface  
42 desert sand in Kuwait, with four kinds of crude oil (Benzene, AI-Ritga heavy crude oil,  
43 Rawdatain light crude oil, and AI-Zoor gas oil) with the amount of 2, 4 and 6 wt.% of the  
44 dry sand resembling the actual in-situ circumstances of oil contamination in the area reported  
45 by Kuwait Oil Company in 1991 (Al-Mutairi 1995; Kuwait-Oil-Company 1991a; Kuwait-  
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1 Oil-Company 1991b). The researchers conducted a series of permeability tests with a  
2 constant head on the clean and 6% oil-contaminated sands with a relative density of 60%.  
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4 The results disclosed a reduction of about 20% (from  $1.72 \times 10^{-5}$  m/sec to  $1.38 \times 10^{-5}$  m/sec) in  
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6 the coefficient of permeability due to adding crude oil up to 6% for this reason that water-  
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8 insoluble hydrocarbon compounds can occupy the majority of soil pore volume as a  
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10 fundamental element controlling sand hydraulic conductivity (Budhu et al. 1991).  
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12 Furthermore, the authors utilized a series of modified proctor compaction tests in order to  
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14 evaluate compaction properties of heavy crude oil contaminated Jahra sand. The maximum  
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16 dry density (MDD) and optimum moisture content (OMC) of clean Jahra sand was about  
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18 1900 kg/m<sup>3</sup> and 12%, respectively. Adding further crude oil, up to 4 wt.%, significantly  
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20 improved both MDD and OMC as a result of lubrication effect of oil. MDD and OMC of 4  
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22 wt.% oil-contaminated sand were about 1940 kg/m<sup>3</sup> and 6.9%, respectively, and a decrease of  
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24 approximately 42.5% in OMC was observed after the presence of 4 wt.% of crude oil in the  
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26 sand. In addition, increasing oil content, from 4 wt.% to 6 wt.%, negatively affects the  
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28 compaction curve and its shape transformed to a strange style. In general, it can be said that  
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30 there was a critical value of oil content (4 wt.%) in terms of compaction properties.  
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32 Moreover, based on the results of their isotropically consolidated undrained triaxial tests on  
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34 the clean and 6 wt.% crude oil-contaminated Jahra sand with a relative density of 60%, 6  
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36 wt.% crude oil-contaminated sand at all confining pressures presented smoother behavior  
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38 than the clean ones with no obvious peaks. Additionally, the elastic modulus (E modulus) of  
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40 6 wt.% crude oil-contaminated sand were about half of that of clean sand. Based on a detailed  
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42 investigation into the results of triaxial tests, a typical medium and also dense behavior can be  
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44 attributed to the clean and contaminated sand, respectively. According to the presented results  
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46 of a series of consolidation tests in the form of e-log p curves on clean and 6 wt.% crude oil-  
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48 contaminated Jahra sand (with a relative density of 60%), an increase in sand compressibility  
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1 with the presence of crude oil (6 wt.% of both light and heavy crude oil) could be obviously  
2 observed as a result of lubricant effects of hydrocarbons on the inter-particle sliding and  
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4 slipping of the sand. Precisely speaking, Al-Sanad et al. reported that the compression index  
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6 was 0.03 in the clean sand, and this value increased to 0.06 and 0.07 after 6 wt.% of light and  
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8 heavy crude oil were added into the sand, respectively. In addition, direct shear apparatus was  
9  
10 utilized by Al-Sanad et al. (1995) in order to examine influences of relative density, type, and  
11  
12 amount of the different hydrocarbon contaminants on shear strength of the Jahra sand. In this  
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14 regard, they considered three different relative densities (30%, 60%, and 90%) and three  
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16 different oil contents (2, 4, and 6 wt.%). However, the authors believed that the amount of oil  
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18 contamination did not have significant effects on the angle of internal friction, they reported  
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20 that the maximum reduction in angle of internal friction was about 5-7°. It should be added  
21  
22 here that, at each particular relative density, increasing amount of crude oil in sand  
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24 diminished the angle of internal friction. This reduction was approximately similar in relative  
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26 density of 30% and 60%, but it was slightly less in relative density of 90%.

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29 Following their previous research (Al-Sanad et al. 1995), Al-Sanad and Ismael in 1997  
30  
31 conducted a series of laboratory strength and compressibility tests to evaluate aging effects  
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33 on important geotechnical properties of crude oil-contaminated Jahra sand (Al-Sanad and  
34  
35 Ismael 1997). They prepared several 6 wt.% oil-contaminated soil samples, and left them  
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37 under severe environmental conditions, including wind and high temperature, for about 6  
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39 months. Based on the results of isotropically consolidated undrained triaxial test, it can be  
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41 concluded that initial and tangent E modulus of the fresh contaminated soil are approximately  
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43 half the modulus of clean ones. The moduli of 6-month-aged contaminated sand were clearly  
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45 lower than those of the fresh ones; however, they still remained under moduli of the clean  
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47 sand. This phenomenon indicates a stiffer behavior of aged oil-contaminated sand in  
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49 comparison with the fresh ones. With reference to e-log p curves of consolidation tests on  
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1 aged oil-contaminated Jahra sand, the compressibility of oil-contaminated sand decreased  
2 with time so that compression index ( $C_c$ ) decreased in the first 3 months, and then remained  
3 almost unchanged in the second 3 months. Al-Sanad and Ismael also reported from in their  
4 direct shear tests that angle of internal friction of contaminated sand enjoyed an almost 15%  
5 increase after 6 months. However, the rate of aging-induced changes in angle of internal  
6 friction was significant during the first month (Al-Sanad and Ismael 1997).  
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14 Srivastava and Pandey in 1998 presented results of their geotechnical tests on two Indian oil-  
15 contaminated soil including alluvial soil and sand (Srivastava and Pandey 1998). In this  
16 regard, soil specimens were provided by mixing oil contaminates with soil in various  
17 percentages (0, 3, 6, 9 and 12 wt.%). According to PSD analysis, particle size of both soil  
18 types increased as a result of oil coated particles. Moreover, the authors reported that both  
19 Liquid Limit (LL) and Plasticity Index (PI) of alluvial soil increased by adding oil, but Plastic  
20 Limit (PL) and Shrinkage Limit (SL) diminished. The results of compaction tests revealed  
21 that both MDD and OMC decreased as oil content increased; however, in the case sandy soil,  
22 the reduction in OMC was noticeable. Additionally, with reference to the results of UU  
23 triaxial tests on both alluvial soil and sand, oil contaminant decreased both cohesion and  
24 angle of internal friction of alluvial soil showing the loss of shear strength; however,  
25 cohesion and angle of internal friction of sandy soil firstly enjoyed an increase and then both  
26 of them decreased. According to Srivastava and Pandey, compression index ( $C_c$ ) of all  
27 contaminated soil samples rose as oil content increased.  
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In 2007, Khamehchiyan et al. studied the effects of crude oil contamination on geotechnical properties of clayey and sandy soil collected from a beach area of Bushehr city in Iran (Khamehchiyan et al. 2007). These soil were categorized as SM (silty sand), SP (poorly-graded sand), and CL (lean clay) according to the USCS. The used crude oil was paraffinic in composition and mixed with soil in the amount of 0, 4, 8, 12, and 16 wt.%. With reference to



1 the published results, both MDD and OMC of sandy soil decreased due to crude oil  
2 contamination; however, some previous researchers (Al-Sanad et al. 1995; Meegoda et al.  
3 1998) had the opposite findings for sands in which there was a critical oil content that, before  
4 and after this point, MDD increased and then decreased. Of course, the decrease in MDD of  
5 poorly-graded sand was very moderate owing to considerable large pore spaces into soil  
6 structure (Khamsehchiyan et al. 2007). Moreover, the shape of compaction curves of SP sand  
7 obviously altered from a double-peak type to a bell shape as oil content increased (see also  
8 (Lee and Suedkamp 1972)). Precisely speaking, it can be mentioned that hydrophobic  
9 hydrocarbon molecules limit the contact between water and soil grains, and therefore, any  
10 increment in oil concentration reduces the capillary tension force (Franklin et al. 1973),  
11 thereby changing the shape of compaction curves. Khamsehchiyan et al. also claimed that it is  
12 not logical to use usual methods (ASTM-D-4959 (ASTM 1999)) for determining Atterberg  
13 Limits in the case of fine-grained oil-contaminated soils since oil can evaporate in a wide  
14 range of temperature, even under room conditions (Sleep and McClure 2001), and this  
15 phenomenon can alter the composition of hydrocarbon compounds in the structure of  
16 hydrocarbon-contaminated soil (Khamsehchiyan et al. 2007; Rahman et al. 2007). The amount  
17 of remained high viscose oil after evaporation procedure can be greatly influenced by size,  
18 adhesion, cohesion, and thermal conductivity of soil particles as well as thermal properties of  
19 hydrocarbon compounds (Alrtimi et al. 2016; Fine et al. 1997). Khamsehchiyan et al. reported  
20 that crude oil evaporation in clayey soil (CL) is more serious than the other soil as a result of  
21 its slower heat transfer (Zhu et al. 2015). Moreover, it should be noted that thermal  
22 conductivity of soil can be related to its Specific Surface Area (SSA), and soil with higher  
23 SSA have lower thermal conductivity (Łydźba et al. 2014). In addition, from their results, it  
24 is also apparent that, at constant environmental conditions, crude oil evaporation diminished  
25 in contaminated soil with higher amounts of crude oil, and it may be associated with thermal

1 conductivity, adhesion and/or cohesion properties of soil and oil hydrocarbon compounds  
2 (Khamehchiyan et al. 2007). The following equation has been proposed by Khamehchiyan et  
3  
4 al. to determine the water content of an oil-contaminated soil after oil evaporation process:  
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$$6 \quad \omega(\%) = (1 + mn) \frac{W_t}{W_d} - (1 + n) \quad (1)$$

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10 In which  $W_t$ ,  $W_d$ ,  $m$ , and  $n$  are wet weight of contaminated soil, dry weight of contaminated  
11 soil, oil residual after drying, and oil content before drying, respectively (Khamehchiyan et  
12 al. 2007).  
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16 Atterberg Limits tests were conducted on CL contaminated samples in order to evaluate  
17 alterations in PL and LL as a result of crude oil contamination in the structure of clayey soils.  
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19 According to the reported results by the authors, both limits decreased with increasing crude  
20 oil content due to this fact that crude oil molecules are non-polar, and also clayey soils do not  
21 show plasticity with non-polar fluid (Kaya and Fang 2000; Quigley and Fernandez 1991;  
22 Ratnaweera and Meegoda 2006). Furthermore, it should be considered that, in this  
23 experimental program, dry clayey soil samples were firstly mixed thoroughly with crude oil,  
24 and this procedure led to uniformly contaminated soil samples in which crude oil molecules  
25 properly surrounded soil particles and weaken probable relationships between clayey  
26 particles and polar water molecules.  
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41 Based on the results of direct shear tests on clayey and sandy soil (Khamehchiyan et al.  
42 2007), it can be said that crude oil contamination enhanced angle of internal friction of CL  
43 samples from  $26^\circ$  for clean sample to  $34.5^\circ$  in 16 wt.% contaminated specimen, and this trend  
44 was intensified by adding more crude oil rather than 12%. Contrarily, in the case of sandy  
45 soil, oil contamination reduced the amount of angle of internal friction so that friction angle  
46 of almost  $34^\circ$  in clean samples reached to around  $26^\circ$  in 16 wt.% contaminated specimens for  
47 both sand. Moreover, a significant reduction of about 80% in cohesion of CL was also  
48 observed by the authors as a result of adding 16 wt.% of crude oil so that the majority of this  
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1 change was taken place after mixing Cl with 16 wt.% of crude oil. Of course, there were no  
2 noticeable changes in the hydrocarbon-induced cohesion of sand as a result of raising amount  
3 of crude oil. Peak shear strength of all crude oil-contaminated soils were lower than those of  
4 uncontaminated ones; however, the amount of influences imposed by the contamination and  
5 its trend were dependent on soil type in this study. Generally speaking, permeability of all  
6 oil-contaminated soils experienced a reduction in their amounts as crude oil content increased  
7 (Anderson et al. 1985; Foreman and Daniel 1986; Uppot and Stephenson 1989). According to  
8 a series of UCS tests conducted by Khamehchiyan et al., it can be said as a conclusion that  
9 both CL and SM soil suffered from a significant decrement in their uniaxial compressive  
10 strengths. In more detail, UCS of CL fell from 3.6 kg/cm<sup>2</sup> to 0.6 kg/cm<sup>2</sup> as crude oil content  
11 rose up to 16 wt.% in clayey soil. Similarly, increasing crude oil content to 16 wt.% in SM  
12 sample could diminish uniaxial compressive strength of sand from 0.94 kg/cm<sup>2</sup> to 0.36  
13 kg/cm<sup>2</sup>.

14 In 2010, Jia et al. conducted extensive experimental studies about influences of hydrocarbon  
15 contamination on geotechnical properties of three different soil collected form Hai-gang  
16 region in Yellow River Delta, China (Jia et al. 2010). This area is a well-known submarine  
17 delta which is covered by river sedimentation, and has been influenced by hydrocarbon  
18 contamination during huge oil exploitation. The authors did a series of conventional  
19 geotechnical tests including PSD analysis, Atterberg limits, compaction, and direct shear test  
20 as well as ultraviolet-spectrophotometer assay to analyze oil content in the collected samples.  
21 To obtain in situ samples, the researchers planned 5 survey lines and 25 test points which had  
22 30m transverse and 20m longitudinal intervals, respectively. The collected hydrocarbon-  
23 contaminated soil samples were categorized into three groups in the lab based on their oil  
24 contents named as light-polluted (L), heavy-polluted (H), and medium-polluted (M)  
25 specimens. If oil content of a soil sample was less than 0.1mg/g, it was light-polluted, and if

1 the content was more than 1mg/g, it was a heavy-polluted sample. Moreover, if oil content of  
2 a sample fell between 0.1mg/g and 1 mg/g, it was a medium-polluted sample. According to  
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4 PSD analysis and plasticity indices, the provided samples were silty soil. Based on PSD  
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6 curves presented by (Jia et al. 2010) for all of light-, medium-, and high-polluted specimens,  
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8 it can be inferred that hydrocarbon contaminants coating soil grains could create bigger-sized  
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10 hydrocarbon-coated particles. Additionally, according to fine grain size analysis, the number  
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12 of clay-sized grains (<0.005) in heavy-polluted samples is surprisingly higher than the  
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14 content in light-polluted ones. The authors believed that due to dissolution of organic and  
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16 inorganic composite colloids, free oxide colloid sands, and soluble salts in hydrocarbon  
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18 contaminant, powerful contacts between soil particles were weakened and/or omitted.  
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20 Therefore, this trend led to simply disperse soil particles and to increase the number of clay-  
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22 sized grains, especially in heavily-polluted samples (Srivastava and Pandey 1998). Likewise,  
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24 according to Atterberg limit tests conducted by Jia et al. (2010), all of Atterberg limits  
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26 including LL, PL, and PI increased with increasing oil content to 14 mg/g in contaminated  
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28 soil. Correctly, the value of LL enjoyed an almost 66% increment from about 24% to 40%,  
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30 while this growth was about 33% for PL, from approximately 17% to 23%. Consequently, it  
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32 can be concluded that PI could increase from 6.4% to about 18% as oil content grew to 14  
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34 mg/g. Based on the literature regarding the effects of organic pore fluid on the amount of  
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36 Atterberg limits in fine-grained soil, it is logical to anticipate apparent influences of  
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38 hydrocarbon contamination on Atterberg limits of clayey soil (Quigley and Fernandez 1991).  
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40 In simple words, hydrocarbon compounds of crude oil as high viscose pore fluid make it  
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42 difficult for soil skeleton to be altered by water, and consequently increases the value of  
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44 Atterberg limits (Kaya and Fang 2000).  
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55 Jia et al. also reported the results of their compaction tests in terms of both compression  
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57 coefficient and modulus under laterally constrained compression with cyclic loading (Jia et  
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1 al. 2010). In this regard, it can be observed in their findings that although compression  
2 coefficient increased significantly as the amount of oil was raised in soil, compression  
3 modulus did not follow the same trend. This alteration can be attributed to the destructive  
4 effects of oil contamination on soil structure, thereby increasing the number of soil pores and  
5 softening soil stress-strain behavior. A precise survey on the published results of direct shear  
6 tests conducted by Jia et al. in 2010 reveals that both friction angle ( $\varphi$ ) and cohesion (C) do  
7 not present any correlation with oil content under loads of 50, 100, 150, and 200 kPa.  
8 Considering this fact that strength behavior of fine-grained soil is fundamentally depended on  
9 cohesion (Boulanger et al. 1998; Das 2015; Huang et al. 1999; Sridharan and Prakash 1999),  
10 the authors believed that the hydrocarbon-induced viscosity and cohesion in the soil pores  
11 could compensate the weakened contacts among soil particles, and eventually the  
12 combination of these contrary conditions resulted in a stable trend. However, according to the  
13 in situ penetration tests, Jia et al. (2010) reported that soil strength was reduced by increasing  
14 oil content. With the aim of examining contamination effects on microstructure of soil, Jia et  
15 al. also provided and compared some micro scale pictures of light-, heavy-, and medium-oil-  
16 contaminated silty soil (Jia et al. 2010). Based on their provided images, the light oil-  
17 contaminated sample still has its inter-particle contacts structure with clear pores around  
18 grains; however, the heavy oil-contaminated one presents a granular and honeycomb texture  
19 (Izdebska-Mucha and Trzeciński 2008; Izdebska-Muchaa et al. 2011).

20 Nazir in 2011 conducted an experimental study to examine long-term effect of motor oil  
21 contamination, in 1, 3, 6, 12, and 24 months after contamination took place, on geotechnical  
22 properties of over-consolidated undisturbed clay samples (CH according to the USCS) which  
23 were extracted from the depth of 6.00 m of the drilled boreholes in Tanta area, Egypt (Nazir  
24 2011). The soil samples included a mixture of sand (12.6 wt.%), silt (14.2 wt.%), and clay  
25 (73.2 wt.%) (Based on wet mechanical analysis (ASTM 2007)) in which the clay section

1 included montmorillonite (72 wt.%), kaolinite (18.2 wt.%), and illite (9.8 wt.%) according to  
2 XRD analysis. Atterberg limits, UCS, and consolidation tests were then conducted by the  
3 researcher to evaluate the influences of motor oil on engineering properties of the soil. Based  
4 on the published results, both LL and PL significantly decreased with passing about 3 months  
5 after the contamination commenced, and afterwards both limits did not show considerable  
6 alterations with time. According to (Nazir 2011) and (Khomehchiyan et al. 2007), in the case  
7 of organic pore fluid like motor oil, the physicochemical changes in soil microstructure, as a  
8 result of low dielectric constant value of organic pore fluid, can make the clay behave  
9 approximately like cohesionless materials, and ultimately lessen LL. Moreover, Nazir utilized  
10 a back calculation method to determine the permeability of clean and motor oil-contaminated  
11 clay samples from the results of the consolidation tests. According to the results indicated by  
12 (Nazir 2011), at a lower stress, around the pre-consolidated stress (100 kPa), the value of  
13 coefficient of permeability at 24-month oil-contaminated clay was approximately 3 times  
14 higher than that of clean clay, and this significant increase can be associated with the lower  
15 dielectric constant of oil making shrinkage in double layers around clay particles and creating  
16 macrospores and macrocracks in clay with time (Izdebska-Mucha and Trzeciński 2008) which  
17 could be resulted in an increase in the coefficient of permeability. In addition, beyond the  
18 pre-consolidated stress, there was not obvious alteration in the coefficient of permeability  
19 caused by aging, and the coefficient of permeability of all aged samples including 24-month  
20 oil-contaminated clay similarly pursued unchanged trends as applied stress increased. The  
21 influences of continuation of the contamination on the coefficient of permeability were also  
22 presented by (Nazir 2011) for various stress ranges. With reference to the published  
23 information, it can be expressed that, at lower stresses (100 and 200 kPa), the effects of  
24 duration period of contamination were much more significant than at higher stresses (400 and  
25 800 kPa). However, after passing a month, the coefficient of permeability in all stress values  
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1 remained almost constant (Nazir 2011). The observed changes in permeability of motor oil-  
2 contaminated clay can be related to the lower dielectric constant value of motor oil as pore  
3 fluid, and may be explained by the double layer theory in which a reduction in the dielectric  
4 constant value of pore fluid will decrease thickness of the double layers around clay particles  
5 (Bowders and Daniel 1987; Khomehchiyan et al. 2007; Nazir 2011). Nazir also reported the  
6 effects of continuation of motor oil contamination on UCS of the clay samples. A serious  
7 decline in UCS was observed during the first 6 months after contamination occurred, and  
8 there was not any remarkable change in the strength during the next 18 months. In this  
9 research, the authors determined initial compression index ( $C_c$ ), swelling index ( $C_r$ ), and pre-  
10 consolidated pressure using Cassgrande method (Cassgrande 1936) as well as over  
11 consolidation ratio (OCR) using back calculation process from stress-strain relationships. In  
12 general, OCR was not sensitive to the duration period of contamination; however,  $C_c$  and  $C_r$   
13 showed different behaviors so that, during the first 6 months after contamination, motor oil  
14 contamination made  $C_r$  almost double, and thereafter  $C_r$  followed a constant trend (the next  
15 18 months). On the other hand,  $C_c$  also enjoyed a similar increase to  $C_r$  during the first 3  
16 months, and then reached stability.

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39 In 2013, Khosravi et al. studied the effects of gas oil contamination on some geotechnical  
40 properties of pure kaolinite (Low plastic clay (CL) according to the USCS) via an extensive  
41 experimental program including Atterberg limits, consolidation, direct shear, and unconfined  
42 compression tests as well as scanning electron microscopy (SEM) (Khosravi et al. 2013). The  
43 used gas oil had a density of 0.8-0.84 at 25°C, and was provided by National Iranian Oil  
44 Refining and Distribution Company (NIORDC). The 24-hour oven-dried pure kaolinite was  
45 mixed with gas oil contamination in the amount of 2, 4, 6, 12, 16, and 20 wt.% of the dried  
46 kaolinite. Then, these samples were put into containers, and kept at temperature of about 30°C  
47 for a week to achieve homogenous mixtures. This range of temperature was chosen in the  
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1 experimental plan based on the usual and average conditions in the locations of Iranian  
2 refineries and oil facilities (Khosravi et al. 2013). The amount of gas oil evaporation from the  
3 contaminated clay for about 4 weeks were examined by the authors, and it was found that  
4 evaporation was significant during the first week, and the total evaporated gas oil was  
5 approximately 3% at the end of 4 weeks (considered as a negligible loss by (Khosravi et al.  
6 2013)). Based on the in situ conditions of clayey soil in the vicinity of the refineries and oil  
7 facilities, all mixed gas oil-clay samples were prepared at the identical dry density of 60%  
8 (10.14 kN/m<sup>3</sup>). The researchers suitably employed scanning electron microscopy (SEM) to  
9 evaluate the effects of water and gas oil contamination on the soil structure. They provided  
10 SEM images of clean dry pure kaolinite, clean wet pure kaolinite (with 12 wt.% of water),  
11 gas oil-contaminated dry pure kaolinite (with 12 wt.% of gas oil), and gas oil-contaminated  
12 wet pure kaolinite (with both 12 wt.% of gas oil and 12 wt.% of water). As it can be seen in  
13 Fig. 4, clean dry pure kaolinite had a dispersed fabric (Fig. 4(a)), and even after adding 12%  
14 of water, the moderate dispersed fabric can be still seen in Fig. 4(b). Moreover, it can be  
15 observed in Fig. 4(c) that 12% gas oil-contaminated dry pure kaolinite had a relative  
16 flocculation since individual kaolinite particles were coated by gas oil compounds. Regarding  
17 Fig. 4(d), (Khosravi et al. 2013) reported that the presence of gas oil could improve the  
18 ability of water to create flocculation in the wet kaolinite structure (See also (Quigley and  
19 Fernandez 1991)).

20 According to the Atterberg Limits tests by (Khosravi et al. 2013), both LL and PI of  
21 contaminated clay increased as gas oil content grew up to 12% in which maximum LL and PI  
22 took place. After adding more than 12% of gas oil, both LL and PI experienced a steep  
23 downward trend, and reached an amount less than that of the virgin pure clay. However, in  
24 the case of PL, a very slight reduction was reported. With reference to these facts that both  
25 water and gas oil molecules are immiscible, act as two separate layers or one phase into



1 another, and especially this point that gas oil molecules have no ability to generate polar  
2 covalent bonds with clay particles, it can be stated based on the diffuse double-layer (DDL)  
3 theory (Mojid 2011) that diffuse double-layers won't be expanded by gas oil molecules, and  
4 consequently small amount of water is needed to bring pure clay into plastic condition.  
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6 Regarding the observed different changes in LL and due to viscous nature of the contaminant,  
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LL.

Khosravi et al. also conducted a series of standard consolidation tests on gas oil-contaminated pure Kaolinite, and reported some changes in compression index ( $C_c$ ) and swelling index ( $C_r$ ). As gas oil content increased,  $C_r$  remained almost constant and  $C_c$  decreased which can be explained using the surface energy available at the gas oil–water interface (Burland 1990; Chen et al. 2000). A large surface tension provided by the surface energy at the interface can combine water droplets and make water drainage to decrease. With reference to SEM images of wet pure kaolinite with and without gas oil contamination, it can be inferred that wet pure kaolinite has more pore spaces and shows higher  $C_c$ . Based on the published results of direct shear tests on contaminated pure Kaolinite with 2, 6, 12, 16, and 20 wt.% of gas oil, it was observed that hydrocarbon contaminants imposed negligible reduction in soil friction angle owing to lubrication effects of gas oil compounds; however, significant influences were observed on the cohesion of clayey soil, especially for gas oil percentages greater than 12 wt.%, as result of a combination of the van der Waals forces and suction in gas oil-clay particle interfaces. As an overall analysis, it can be concluded that shear strength of the kaolinite, calculated using the Mohr-Coulomb failure criterion, was not considerably

1 influenced by gas oil contamination. However, at the same embedded amount of water or gas  
2 oil, gas oil-contaminated dry kaolinite soil showed higher shear strength compared with wet  
3 clean kaolinite soil due to this accepted fact that flocculated soil structure has higher shear  
4 strength than dispersed one (See also (Quigley and Fernandez 1991)). According to  
5 unconfined compression tests conducted by (Khosravi et al. 2013), it is obvious that, in all  
6 contamination contents, undrained shear strength of gas oil-contaminated Kaolinite behaved  
7 linearly before reaching its maximum. Additionally, adding more oil content, up to 12 wt.%,  
8 into soil made shear strength increase gradually, and further oil concentration (>12 wt.%) had  
9 an opposite effect so that 16 wt.% gas oil-contaminated Kaolinite showed a lower peak shear  
10 strength in comparison to Kaolinite with 12 wt.% of contamination.  
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24 In another research in 2013, Ijimdiya evaluated effects of hydrocarbon contamination on  
25 some geotechnical properties of lateritic soil which was reddish brown and collected from the  
26 depth of 0.5 m below the ground level of a burrow pit in Shika, Zaria, Nigeria (Ijimdiya  
27 2013). This soil was classified as A-6 (16) and CL according to the AASHTO and the USCS,  
28 respectively. The used oil as hydrocarbon contamination was waste motor oil provided by  
29 Oando lubrication workshop located near main campus of Ahmadu Bello University, Zaria,  
30 Nigeria. The authors conducted some PSD analyses on clean and contaminated soil, and  
31 found out that contamination could significantly reduce the number of clay-sized particles in  
32 clayey soil because hydrocarbon compounds have the ability to agglomerate soil particles and  
33 to form bigger-sized aggregates, clods, and crumbs which was in a fair agreement with the  
34 relevant results of (Srivastava and Pandey 1998). The particle accumulation was intensified  
35 by increasing oil content from 2 to 6 wt.% which was also claimed by (Jia et al. 2010). Based  
36 on the reported effects of adding waste motor oil contaminant up to 8 wt.% on UCS of clayey  
37 soil, it was observed that UCS values increased about 20.33% due to addition of 2 wt.% of  
38 oil, and then followed a gradual reduction of about 45.20% (compared with its peak value) at  
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1 8 wt.% of oil. It can be explained that primary increase in UCS was due to rearrangement of  
2 the coated soil particles and also improvement in inter-particle bonding. However, the  
3 following reduction in the UCS was as a result of improving lubrication between soil  
4 particles at higher oil contents. Regarding influences of oil content on void ratio of soil under  
5 different loadings (50, 100, 200, 400, 800, 1600 kN/m<sup>2</sup>) in consolidation tests, it can be  
6 totally said that the value of void ratio increased as oil content rose up to 2 wt.% due to  
7 reduction in the number of clay-sized particles in the soil skeleton. Adding more oil up to 6  
8 wt.% caused a steep decrease in the void ratio, and from 6 to 8 wt.%, void ratio of soil  
9 enjoyed a sharp increase (see also (Di Matteo et al. 2011)). Ijimdiya also reported the  
10 influences of oil contamination on coefficient of consolidation ( $C_v$ ) for different loading  
11 conditions. Generally speaking, for all cases,  $C_v$  gradually increased as oil content reached 4  
12 wt.%, and then it enjoyed a significant increase, and peaked at 6 wt.%; however, adding oil,  
13 more than 6 wt.%, caused a rough decrease in  $C_v$  again (Ijimdiya 2013). It can be said that the  
14 increase in  $C_v$  was due to time-dependent primary soil settlement and extrusion of oil from  
15 the soil matrix under loading. Moreover, the next steep decrease in  $C_v$  at higher oil contents  
16 may be owing to simultaneous consolidation and compressibility process as well as oil  
17 extrusion.

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41 In 2014, Akinwumi et al. examined influences of oil contamination (2-10 wt.%) on Atterberg  
42 limits, strength, and permeability of a lateritic clay (A-7-6(7) and sandy lean clay (CL)  
43 according to the AASHTO and the USCS) collected from a borrow pit located in Ogun State  
44 in southwestern Nigeria (Akinwumi et al. 2014a). The researchers carried out sieve and  
45 hydrometer analyses on uncontaminated soil, and also specific gravity, Atterberg limits,  
46 compaction, unsoaked and soaked CBR as well as permeability tests on both uncontaminated  
47 and contaminated soil. The primary specific gravity, PI, MDD, OMC, coefficient of  
48 permeability, unsoaked and soaked CBR were 2.51, 18.0%, 18.2 kN/m<sup>3</sup>, 15.3%,  $8.24 \times 10^{-6}$   
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1 cm/s, 18%, and 10%, respectively. Due to lower specific gravity of crude oil in comparison  
2 with the clean soil, specific gravity of contaminated soil was reasonably lower than the  
3 uncontaminated one, and, with an increase in the amount of contamination, the value of  
4 specific gravity gradually decreased. Based on the authors' report, all of PL, LL, and PI were  
5 progressively increased as crude oil was added to the soil. Considering all of plasticity charts,  
6 AASHTO, and USCS together, it was found out that after adding 10 wt.% of crude oil into  
7 the soil which was primarily classified as A-7-6(7) and CL, it was altered into A-7-5 and an  
8 organic soil with significant plasticity (OH). Moreover, as a result of expansion of the  
9 thickness of the diffuse double layer due to crude oil contamination, under the same  
10 compaction energy, it was not possible to reach the identical MDD in both uncontaminated  
11 and contaminated samples. Therefore, it was seen in the results that increasing the amount of  
12 crude oil increased MDD, and gradually decreased OMC. Moreover, due to depositions of  
13 big molecules of crude oil into the soil pores reducing soil pore space, adding crude oil into  
14 the soil caused a progressive decrease in its permeability. In 2014, again, Akinwumi et al.  
15 evaluated effects of waste oil engine contamination (2-10 wt.%) on some engineering  
16 properties of the same lateritic clay (Akinwumi et al. 2014b). The uncontaminated soil had a  
17 low amount of plasticity, CBR, and also permeability. Due to the lower specific gravity of  
18 waste oil engine in comparison with the soil, as the amount of oil contaminant increased in  
19 the soil structure, the specific gravity of the contaminated soil decreased. Moreover, when oil  
20 content grew, LL and PI increased as well, but PL decreased as a result of interlayer  
21 expansion of clay mineral caused by hydrocarbon compounds of waste oil engine. Based on  
22 the results of standard proctor compaction tests, it was also observed that OMC and MDD  
23 decreased as oil content rose since hydrocarbon compounds surrounding each clay particle  
24 prevented interaction of clay particles and increased thickness of diffuse double layers which  
25 could be responsible for decreasing OMC and MDD, respectively. The authors also

1 introduced the amount of 6 wt.% and 8 wt.% of waste oil engine as the limits for approaching  
2 maximum soaked and unsoaked CBR in this contaminated soil, respectively. It should be  
3 mentioned, however, that adding more oil beyond these limits increased the lubricant effects  
4 of oil contaminant on the friction between soil particles, and decreased strength of soil.  
5  
6 Similar to the other relevant literature (Khomehchiyan et al. 2007; Silvestri et al. 1997), a  
7 reduction in soil permeability due to oil contamination was also observed in this study.  
8  
9 In addition, Onyelowe in 2015 studied influences of pure crude oil contamination on the  
10 properties of Amaoba Lateritic soil (A-2-6 based on the AASHTO) collected from Amaoba  
11 borrow pit in Nigeria (Onyelowe 2015). The author evaluated the behavior of contaminated  
12 soil via several laboratory tests including PSD, water content, specific gravity, shear strength,  
13 compaction, Atterberg limit, CBR, and consolidation tests. According to the author, LL of  
14 soil decreased from 40% to 38% with embedding 2 wt.% of crude oil, and then increased by  
15 46% as a result of adding more crude oil up to 6 wt.%. Additionally, the author believed that  
16 a reduction in shear strength due to soil contamination might be associated with this fact that  
17 hydrocarbon compounds as non-polar liquid can increase the intermolecular force between  
18 soil particles, and accordingly improve shear strength; however, a further increase in oil  
19 content can act as a barrier between soil particles, and reduces shear strength. According to  
20 the results of standard proctor compaction tests (ASTM-D698, method A (ASTM 1999)), it  
21 can be said that with an increase in the amount of crude oil, there was a slight decrease in  
22 MDD and OMC. It is worth noting that the author figured out that the applicable amount of  
23 oil contamination which soil could hold under compaction and loading process was 2 wt.%  
24 (Onyelowe 2015) so that for the oil percentages more than 2 wt.%, excess crude oil  
25 permeated out of the samples (see also (Khomehchiyan et al. 2007)). As a significant  
26 advantage in the pavement industry, CBR was considerably increased by about 7 times as  
27 pure crude oil was added in soil up to 6 wt.%. (Meegoda 1992; Meegoda et al. 1998).  
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### 3.2. Review summary

#### 3.2.1. Materials and methods

With reference to the information presented in Table 5, it can be obviously observed that crude oil has been the most used hydrocarbon. To add to that, in some research, motor oil, gasoline, and diesel were used as hydrocarbon contaminants as well. It should be also mentioned that the amount of hydrocarbons which were used to provide contaminated specimens has been approximately in a range of 2 to 30 wt.%. The most considered range of contamination, however, was between 2 to 10 wt.%. Furthermore, some particular hydrocarbon-based compounds including bitumen, benzene, and kerosene were also examined in some research (Al-Sanad et al. 1995; Al-Sanad and Ismael 1997; Ola 1991; Singh et al. 2008). More importantly, up to now, various types of soil have been considered as the host medium for hydrocarbon contaminants (Table 2). On this subject, it can be articulated that both fine- and coarse-grained soils have been taken into account in the literature, and suitable information were presented by the investigators regarding possible effectiveness of hydrocarbon contaminations on geotechnical properties of soils (Table 6). More importantly, it should be stated that almost a majority of methods used to assess geotechnical properties of hydrocarbon-contaminated soils in the literature were basic experiments and tests (Table 6), and it is really needed to use advanced testing apparatus in the future endeavors to deeply evaluate the influences of this kind of contamination on engineering properties of soils.

#### 3.2.2. Soil microstructure and particle size distribution

In the case of fine-grained soils, hydrocarbon-induced enlargement in soil grain size along with a reduction in the number of clay-sized grains has been repeatedly reported by various researchers based their SEM and PSD analyses so far (Ijimdiya 2013; Jia et al. 2010; Nazir

1 2011; Talukdar and Saikia 2013). However, there were some contrary observations in the  
2 literature as well. (Jia et al. 2010), for example, reported that the number of clay-sized  
3 particles increased due to a hydrocarbon contamination so that hydrocarbon compounds have  
4 the ability to agglomerate soil particles and to form larger sized aggregates. In addition,  
5 probable dissolution of organic and inorganic composite colloids and soluble salts in  
6 hydrocarbon pollutants as pore fluid can make other changes in soil microstructure. In more  
7 details, substantial changes in surface characteristics and interactions of clayey particles as  
8 well as fabric of fine-grained soils can be caused by hydrocarbon compounds. Hydrocarbon-  
9 coated clay particles have more hydrophobic nature in comparison with hydrophilic surfaces  
10 of clean clay particles, and hydrocarbon compounds are able to create adhesion among clayey  
11 particles, thereby restricting effective range of electrostatic repulsive forces. Precisely, in a  
12 far distance from the coated surface of contaminated clay, attractive forces are dominant;  
13 however, lower electrostatic repulsive forces still exist among particles in the vicinity of clay  
14 surface. Generally, hydrocarbon-contaminated fine-grained soils have a flocculated fabric  
15 with more Edge-to-Face (EF) contacts, but, in clean ones, Face-to-Face (FF) and Edge-to-  
16 Edge (EE) contacts are prevalent that generate a dispersed and oriented fabric. All in all, the  
17 probable hydrocarbon-induced changes in microstructure of fine-grained soils have been  
18 summarized by the authors in Table 7. However, the degree of alterations is greatly depended  
19 on soil mineralogy and physicochemical properties of hydrocarbons, it is reasonable to  
20 observe different trends in comparison with the conclusion provided in Table 7.

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In the case of coarse-grained soils, hydrocarbon compounds surrounding soil particles are  
able to shape new microstructures in soils with hydrocarbon-coated aggregates, and these  
alterations have been reported in several written works (Akinwumi et al. 2014a; Al-Sanad et  
al. 1995; Srivastava and Pandey 1998; Talukdar and Saikia 2013). Due to this well-known  
fact that geotechnical behavior of coarse-grained soils is fundamentally based on physical

1 interactions among soil particles, having a clear-cut knowledge about hydrocarbon-induced  
2 influences on microstructures of soils may be beneficial to understand engineering behavior  
3 of coarse-grained soils. To this aim, SEM images (captured by KYKY – EM3200, China) of a  
4 type of natural sand, in both clean and hydrocarbon-contaminated conditions, have been  
5 provided by the authors in Fig. 5. The used sand was Firoozkooh sand (angular silica sand)  
6 which was collected by Silica Sand MFG Company from the natural silica sand mines located  
7 near Firoozkooh city in Tehran province of Iran. Moreover, the hydrocarbon contamination  
8 was a type of light crude oil provided by West Oil and Gas Production Company (WOGPC)  
9 of Iran. As it can be obviously seen in Fig. 5 (a and b), the deposition of hydrocarbon  
10 compounds into sand can bring about considerable effects on its microstructure. These  
11 alterations may be explained in two aspects. On one hand, hydrocarbon compounds can  
12 create a viscous layer coating surface of each sand particle (Fig. 5(c and d)), and on the other  
13 hand, the contaminants have the abilities to surround contact areas among sand particles and  
14 also fill empty spaces within the particles (Fig. 5(e and f)). Regarding physical effects of  
15 hydrocarbons on surface characteristics (e.g. roughness) of sand particles which are greatly  
16 dependent on hydrocarbon amount, SEM images of clean and contaminated Firoozkooh sand  
17 with 4, 8, and 12 wt.% of light crude oil have been presented in Fig. 6. In this regard, it can  
18 be generally stated that gradually increasing the amount of hydrocarbon compounds can  
19 create hydrocarbon layers around particles and contacts. Thereafter, adding more  
20 hydrocarbons can make these layers thicker, and also fill more empty pores in sand structure.  
21 It seems that, in lower amounts of contaminants, the layers surrounding sand particles have  
22 the ability to create cohesion between particles and to sustain particles together forming a  
23 stronger structure. However, this positive effect may be accompanied by influential impacts  
24 on friction among particles, especially in smaller amounts of hydrocarbons which do not  
25 influence surface roughness (Fig. 6(b)). Seemingly, adding further hydrocarbon into sand can  
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1 almost cover surface roughness completely, and swiftly eliminate this frictional behavior  
2 (Fig. 6(c)). Moreover, increasing the amount of crude oil weakens the induced cohesion in  
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4 the next steps so that the completely hydrocarbon-coated sand particles now are effortlessly  
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6 sliding and slipping around each other creating a loose sand structure Fig. 6(d).  
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9 Regarding PSD of hydrocarbon-contaminated soils, it may be generally concluded that the  
10 presence of hydrocarbon compounds into soil structures can fundamentally change soil  
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12 microstructure with new characteristics. Certainly, the degree and way of changes are greatly  
13  
14 depended on soil type (fine- or coarse-grained soils) and hydrocarbon properties such that  
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16 slightly bigger-sized grains and a flocculated fabric are the main characteristics of fine- and  
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18 coarse-grained soils, respectively.  
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### 26 *3.2.3. Atterberg Limits*

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28 One of the important characteristics of fine-grained soils contaminated by hydrocarbon  
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30 compounds has been Atterberg limits. In a more general sense and based on an overall look  
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32 at some relevant research (Akinwumi et al. 2014a; Akinwumi et al. 2014b; Alhassan and  
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34 Fagge 2013; Jia et al. 2010; Kermani and Ebadi 2012; Khamehchiyan et al. 2007; Khosravi et  
35  
36 al. 2013; Nazir 2011; Pusadkar and Bharambe 2014; Rahman et al. 2010; Solly et al. 2015;  
37  
38 Srivastava and Pandey 1998; Ukpong and Umoh 2015; Walia et al. 2013), the authors are not  
39  
40 able to find a comprehensive trend describing the effects of hydrocarbons on these limits. To  
41  
42 elucidate this fact, the authors have approximately accumulated all the data provided in the  
43  
44 literature regarding both LL and PI of hydrocarbon-contaminated soils in Fig. 7. As it can be  
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46 obviously seen (Fig. 7(a)), LL of hydrocarbon-contaminated soils were placed within a  
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48 specific range of percentages; however, all of the determined PI were somehow scattered  
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50 (Fig. 7(b)) and there was not an expressive trend to present. However, in each particular  
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52 research, it could be possible for the authors to draw a specific tendency for the limits. Based  
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1 on DDL theory, most hydrocarbon compounds, as non-polar fluid, are immiscible in water  
2 and acting as two separated phases (or a phase into another), and won't be able to create  
3 bonds with clay particles (see also (Khosravi et al. 2013)). Moreover, it should be noted that  
4 the thickness of DDL may be affected by various characteristics of pore fluid. More  
5 importantly, the thickness decreases with increase in valency, and also it is significantly  
6 influenced by viscosity. When hydrocarbon compounds are added to fine-grained soils, their  
7 viscosity may be also affected, thereby altering the thickness of DDL. In general, these  
8 factors may result in not expanding diffuse double-layers around clay particles in the  
9 presence of hydrocarbon compounds, and soil plasticity has to take place in different amounts  
10 of water, compared with clean soil, thereby making an alteration in PL. However, regarding  
11 LL in hydrocarbon-contaminated soils, hydrocarbon molecules forming thin viscous layers  
12 surrounding clay particles make LL to change. In addition, it is beneficial to consider impacts  
13 of weathering process on the assessment of soil plasticity since physicochemical properties of  
14 hydrocarbon compounds may be influenced by weathering which are probable to occur in a  
15 wide range of environmental conditions (Al-Sanad and Ismael 1997; Nazir 2011). Moreover,  
16 various parameters including size, hydrocarbon-induced adhesion, and cohesion  
17 (Khomehchiyan et al. 2007; Nazir 2011; Sleep and McClure 2001). All in all, as it can be  
18 inferred based on the aforementioned explanation, certain impacts of hydrocarbon on  
19 Atterberg limits of soil are controversial, and there has not been a comprehensive study  
20 focusing on this subject. As it is highly dependent to soil/hydrocarbon characteristics, it is  
21 greatly suggested to carry out apt research centering on the effects of hydrocarbon  
22 contaminants on Atterberg limits of different types of soil.

#### 3.2.4. Hydraulic conductivity

1  
2 It can be generally discussed herein that hydrocarbon contaminations reduces hydraulic  
3  
4 conductivity of soils (Akinwumi et al. 2014a; Akinwumi et al. 2014b; Al-Sanad et al. 1995;  
5  
6 Budhu et al. 1991; Cook et al. 1992; Foreman and Daniel 1986; Khamehchiyan et al. 2007;  
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8 Meegoda and Rajapakse 1993; Puri 2000; Puri et al. 1994; Rahman et al. 2010; Shin and Das  
9  
10 2000; Siang et al. 2014; Silvestri et al. 1997; Singh et al. 2008; Singh et al. 2009; Tuncan and  
11  
12 Pamukcu 1992; Uppot and Stephenson 1989). Totally, deposition of hydrocarbon compounds  
13  
14 into soil pores, as influential elements governing hydraulic conductivity of soils, considerably  
15  
16 decreases soil permeability. Fig. 8 presents the amount of hydrocarbon-induced alterations in  
17  
18 coefficient of permeability of soil reported by the aforementioned studies. As it was pointed  
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20 by an ellipse on Fig. 8, increasing amount of hydrocarbons effectively intensifies the degree  
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22 of changes in permeability, and the majority of these changes varied in a range of 20 to 80%.  
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#### 3.2.5. Compaction behavior

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32 In general, compaction test has been conducted by geotechnical engineers to find out  
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34 optimum moisture content (OMC) of a soil in which, for a particular compactive effort,  
35  
36 maximum dry density (MDD) of soil can be accessible (Das 2015). Due to probable effects of  
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38 pore fluid on soil compaction, several studies have been concentrated so far regarding  
39  
40 compaction behaviors of hydrocarbon-contaminated soils. Table 8 provides a review on  
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42 maximum dry density (MDD) and optimum moisture content (OMC) of hydrocarbon-  
43  
44 contaminated soils. In a more general sense, it can be mentioned that the effects of  
45  
46 hydrocarbon compounds on MDD and OMC are not similar, and various trends may be  
47  
48 addressed according to Table 8. With reference to OMC, it should be stated that, in all  
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50 relevant research (Akinwumi et al. 2014a; Akinwumi et al. 2014b; Al-Sanad et al. 1995;  
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52 Kermani and Ebadi 2012; Khamehchiyan et al. 2007; Onyelowe 2015; Pusadkar and  
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1 Bharambe 2014; Rahman et al. 2010; Silvestri et al. 1997; Srivastava and Pandey 1998;  
2 Walia et al. 2013), with the exception of (Singh et al. 2009), adding hydrocarbon compounds  
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4 could significantly diminish OMC with 4.3% in CL (Akinwumi et al. 2014a) up to 86% in  
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6 poorly graded sand (SP) (Khamehchiyan et al. 2007). However, (Singh et al. 2009) observed  
7  
8 that OMC of both CL and CH soil increased almost by 12 and 22%, respectively, as the  
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10 amount of hydrocarbon content (used motor oil) rose to 9 (wt.%).  
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14 On the other hand, MDD experienced different hydrocarbon-induced changes. In a majority  
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16 of research studies (Akinwumi et al. 2014a; Akinwumi et al. 2014b; Khamehchiyan et al.  
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18 2007; Pusadkar and Bharambe 2014; Rahman et al. 2010; Silvestri et al. 1997; Singh et al.  
19  
20 2009; Walia et al. 2013), as hydrocarbon compounds increased in soils, MDD diminished  
21  
22 accordingly. Moreover, some researchers observed that MDD increased as hydrocarbon  
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24 content rose in soils. For Example, Kermani and Ebadi (2012) reported that MDD of silty soil  
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26 could rise about 5.18% from 1640 to 1725 (kg/m<sup>3</sup>) with adding 12 wt.% of light crude oil  
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28 (Kermani and Ebadi 2012). In addition, a few studies (Al-Sanad et al. 1995; Onyelowe 2015;  
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30 Srivastava and Pandey 1998) reported that as hydrocarbon content increased in soils, MDD  
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32 firstly increased, and then decreased. Meanwhile, it should be noticed that the shapes of  
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34 compaction curves have been also affected by hydrocarbons, and bell shapes or double-peak  
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36 types were pointed in some literature (Khamehchiyan et al. 2007).  
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43 To sum up, it can be stated that in the case of sand, lubrication effects of hydrocarbon  
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45 compounds on interaction between particles can be named as a key element changing  
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47 compaction behavior. However, when hydrocarbon contaminations containing hydrophobic  
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49 compounds are added in fine-grained soils, hydrocarbon compounds with higher molecular  
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51 weight are absorbed onto the grain surfaces and surround soil particles. This process which  
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53 agglomerates soil particles, decreases particle's Specific Surface Area (SSA), and reduces  
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1 bonding strength may be responsible for altering compaction behavior of hydrocarbon-  
2 contaminated fine-grained soils.  
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### 4 5 6 7 *3.2.6. Consolidation characteristics* 8

9 Based on a careful review on the effects of hydrocarbon contaminations on consolidation of  
10 soils, it can be inferred that hydrocarbon-induced changes in consolidation characteristics ( $C_c$   
11 and  $C_v$ ) of soils were highly dependent on types of both soil and hydrocarbon (Al-Sanad et al.  
12 1995; Alhassan and Fagge 2013; Di Matteo et al. 2011; Estabragh et al. 2016; Ijimdiya 2013;  
13 Kermani and Ebadi 2012; Khosravi et al. 2013; Meegoda and Ratnaweera 1994; Nazir 2011;  
14 Onyelowe 2015; Singh et al. 2008; Srivastava and Pandey 1998; Talukdar and Saikia 2013;  
15 Tuncan and Pamukcu 1992). All in all, on one hand, some of these studies stated that  
16 compression index ( $C_c$ ) of soil increased with adding oil content (Al-Sanad et al. 1995; Singh  
17 et al. 2008; Srivastava and Pandey 1998), and on the other hand, a few researchers claimed  
18 the opposite behavior, especially for clayey soils (Alhassan and Fagge 2013; Khosravi et al.  
19 2013; Talukdar and Saikia 2013; Tuncan and Pamukcu 1992). According to the surface  
20 energy method, the surface energy at the hydrocarbon-water interface creates a higher surface  
21 tension on the considered interface, and results in decreasing water drainage from soil  
22 structure. This procedure can reduce the compressibility of clayey hydrocarbon-contaminated  
23 soils. To elucidate both procedures, the hydrocarbon-induced changes in compression index  
24 ( $C_c$ ) of soil were presented in Fig. 9. Increasing and decreasing effects of hydrocarbon  
25 compounds on  $C_c$  were indicated by positive and negative percentages on the vertical axis.  
26 Moreover, according to the provided trendline in Fig. 9, it can be generally said that as  
27 hydrocarbon content increases, the seriousness of changes in  $C_c$  is also intensified.  
28 Furthermore, regarding coefficient of consolidation ( $C_v$ ), it can be generally stated that,  
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1 approximately in all related literature, hydrocarbon contaminations could diminish the value  
2 of  $C_v$ . However, it was also depended on particular situation of each research.  
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### 6 7 *3.2.7. Angle of internal friction and cohesion* 8

9 The angle of internal friction and also cohesion originated from inter-particle relationships  
10 play important roles in defining engineering behavior of soils. Therefore, the assessment of  
11 hydrocarbon-induced effects on these parameters is a beneficial key to find more about their  
12 geotechnical behaviors. Regarding angle of internal friction, a quick review on the research  
13 studies discussing influences of hydrocarbon compounds on soil friction reveals that,  
14 approximately in all cases, hydrocarbon-based contaminations reduced angle of internal  
15 friction (Al-Sanad et al. 1995; Cook et al. 1992; Evgin and Das 1992; Khamehchiyan et al.  
16 2007; Puri 2000; Shin et al. 2002; Siang et al. 2014; Singh et al. 2008; Srivastava and Pandey  
17 1998). In this regard, angle of internal friction of various hydrocarbon-contaminated soils has  
18 been summarized in Fig. 10(a). Notwithstanding a slight scattering state in the results, it is  
19 possible to draw a trendline showing prevailing direction of hydrocarbon-induced changes in  
20 angle of internal friction so that a gradual reduction in angle of internal friction is obvious as  
21 a result of hydrocarbon contaminations. Moreover, as hydrocarbon concentration increases in  
22 hydrocarbon-contaminated soils, the induced difference between internal friction angle of  
23 clean and contaminated soils also increases (see (Shin et al. 2002)). As it was completely  
24 explained in section 3.2.2, these observations can be associated with lubrication effects of  
25 hydrocarbon compounds on surface roughness of particles, as vital elements creating  
26 frictional behavior of soils, which result in facilitating inter-particle sliding and slipping (Fig  
27 5-6). In this regard, it can be stated that adding further hydrocarbon into soils can  
28 approximately cover surface roughness, and eliminate the existing friction among soil  
29 particles. Additionally, adding crude oil weakens the induced cohesion between soil grains.  
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1 In the case of cohesion, in various research studies (Chew and Lee 2010; Francis 2013;  
2 Kermani and Ebadi 2012; Khamehchiyan et al. 2007; Khosravi et al. 2013; Srivastava and  
3 Pandey 1998), hydrocarbon-induced changes in cohesion of soil have been investigated. On  
4 this subject, their published results were accumulated in Fig. 10(b). As it was depicted, in a  
5 majority of cases, increasing hydrocarbon contamination could diminish the value of  
6 cohesion, especially in clayey soil. However, in a few studies, hydrocarbon-induced  
7 influences were not considerable. In addition, it should be added that hydrocarbon  
8 compounds have the ability to create small amount of cohesion among sand particles owing  
9 to their adhesion capacities (red lines in Fig. 10(b) - see also section 3.2.2) (Khamehchiyan et  
10 al. 2007; Srivastava and Pandey 1998). In general, probable imposed alterations on van der  
11 Waals forces and suction between soil grains as well as creation of hydrocarbon-wet  
12 conditions into soil microstructure may be responsible for reducing cohesion of hydrocarbon-  
13 contaminated fine-grained soils. All in all, the rate of change in cohesion of soils as a result  
14 of hydrocarbon contaminations is highly depended on properties of soil and hydrocarbon  
15 compounds, and this matter must be considered in each assessment.

### 3.2.8. *Unconfined compression strength*

41 In Table 9, the available results of some unconfined compression tests on hydrocarbon-  
42 contaminated soils have been tabulated by the authors in terms of both unconfined  
43 compression strengths ( $q_u$ ) and their corresponding strains ( $\epsilon_q$ ). Due to variations of soil and  
44 hydrocarbon types as well as operating conditions, it is not possible to form a general  
45 tendency about UCS of hydrocarbon-contaminated soils. However, according to the relevant  
46 literature (Ijimdiya 2013; Khamehchiyan et al. 2007; Khosravi et al. 2013; Solly et al. 2015;  
47 Walia et al. 2013), hydrocarbon compounds could bring about diminishing and enhancing  
48 influences on unconfined compression strength of soil. Moreover, in some cases (Ijimdiya  
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2013; Khosravi et al. 2013), as the amount of hydrocarbon rose, UCS firstly enjoyed a gradual increase, and then moderately decreased to the lower values compared to clean soils.

Moreover, Table 9 revealed that the available literature assessing UCS of hydrocarbon-contaminated soils are not sufficient to suitably evaluate the effects of hydrocarbon contaminations on this important geotechnical properties of soil, so it is suggested to comprehensively study the probable effects of hydrocarbon on UCS so as to clarify the issue.

### 3.2.9. Maximum shear modulus ( $G_{max}$ or $G_0$ )

In Fig. 11, the results of the experimental endeavours by (Rajabi and Sharifipour 2017a; Rajabi and Sharifipour 2017b) were depicted which was conducted with the aim of assessing probable influences of hydrocarbon contamination on maximum shear modulus of sand. Two critical amounts of crude oil content was introduced so that up to a critical amount (the first one (here 4 wt.%)), hydrocarbon compounds could moderately increase  $G_{max}$ , and beyond this amount, embedding further crude oil into sand, up to the second critical oil content, made  $G_{max}$  decrease obviously to an amount lower than the virgin one. After the second critical content (here 8 wt.%), the hydrocarbon-induced influences on  $G_{max}$  were insignificant. In this regard, it should be emphasized that the reported study merely focused on the contaminated standard sand, and the effects of hydrocarbon contamination on  $G_{max}$  of different type of soil like sandy soil, clayey soil, etc. can be considered as novel topics of future research.

### 3.2.10. Weathering

As previously explained, weathering process is an influential factor which should be accurately considered in the assessment of hydrocarbon-contaminated soils. In more details, environmental factors have the ability to change physical and chemical characteristics of



1 hydrocarbon compounds in soil via sorption into soil structure, chemical reaction by existing  
2 substances in soil, volatilization into air, microbial degradation, and also dissolution in water.  
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4 Therefore, aging-induced changes in hydrocarbon-contaminated soils should be accurately  
5 examined in addition to the short-term effects of hydrocarbon compounds. However, up to  
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7 now, few research studies were concentrated on long-term effects of hydrocarbon  
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9 contaminations on geotechnical properties of soil. In section 3.1, a brief explanation of  
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11 experimental investigations by (Al-Sanad and Ismael 1997) and (Nazir 2011) about aging  
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13 effects on geotechnical properties of hydrocarbon-contaminated soils were provided by the  
14  
15 authors, and in Table 10, a summary of their results has been presented. In this regard, it can  
16  
17 be inferred that the majority of aging-induced changes in engineering properties of soil took  
18  
19 place during the first three months after contamination occurred. Moreover, Rajabi and  
20  
21 Sharifipour in 2018 carried out a series of bender element test on fresh and aged  
22  
23 hydrocarbon-contaminated sand so as to assess the influences of weathering process on  $G_{max}$   
24  
25 of two types of standard sands (Ottawa sand and Firoozkooh sand) (Rajabi and Sharifipour  
26  
27 2018). According to their results,  $G_{max}$  of both sand types increased obviously due to  
28  
29 environmental conditions up to 6 month, more seriously during the first 2 months. The  
30  
31 authors believed that the weathering-induced changes on maximum shear modulus of  
32  
33 hydrocarbon-contaminated soils are dependent on soil type, oil content, and time. In general,  
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35 it may be reasonable to consider these observable changes only as partial studies, and it really  
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37 needs to be extensively concentrated in future research.  
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#### 4. Conclusions and recommendations

In this paper, a comprehensive review focusing on academic literature regarding geotechnical properties of hydrocarbon-contaminated soils was presented. All in all, the following general conclusions can be inferred.

1. Based on the microstructural characterizations, the presence of hydrocarbon compounds in coarse-grained soil can considerably weaken surface roughness of particles, thereby facilitating sliding and slipping among them. On the other hand, hydrocarbon contaminations may bring about the flocculated fabrics with more Edge-to-Face (EF) contacts, less-oriented structural elements, decomposed aggregates, and bigger-sized particles in fine-grained soils.
2. Being highly affiliated with soil and hydrocarbon specifications, LL and PL of soil may be influenced by hydrocarbon contaminations. Although all the reported limits of hydrocarbon-contaminated soils were placed in specific ranges, there were not crystal-clear trends to be named here describing hydrocarbon-induced changes on these limits.
3. As a frequent observation, almost all published articles declared that the coefficient of permeability of soil gradually diminished as a result of adding hydrocarbon contaminations.
4. With reference to the results of compaction and consolidation tests, it may be predictable that OMC of contaminated soils is lower than that of the clean ones; however, in the case of MDD, the hydrocarbon-induced changes may not be as straightforward as OMC. To add to that, the degree of hydrocarbon-induced changes in compression index ( $C_c$ ) of soil slightly intensified as the amount of hydrocarbon contamination increased in soil structure.
5. According to a general look at the assimilated data regarding angle of internal friction and cohesion of hydrocarbon-contaminated soils, it can be stated that adding hydrocarbon

1 compounds can probably diminish both angle of internal friction and cohesion of soil as a  
2 result of imposing alterations in inert-particle relationships and fabric of soil.  
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4 The authors believe that, notwithstanding a great deal of research allocated to this subject  
5 heretofore, a few cases still exist that need to be concentrated more in details regarding  
6 hydrocarbon-contaminated soils including hydrocarbon-induced changes in microstructures  
7 of both coarse- and fine-grained soils, dynamic behavior of hydrocarbon-contaminated soils,  
8 and long-term influences of hydrocarbon contaminations on geotechnical properties of soils.  
9 More importantly, it should be mentioned here that the majority of research studies  
10 discussing geotechnical properties of hydrocarbon-contaminated soils has been lab-oriented  
11 works, and it really needs to perform comprehensive in-situ surveys in order to confirm  
12 and/or correct the available lab-oriented experimental findings.  
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**List of Tables:**

**Table 1.** The largest hydrocarbon contaminations in history since 1900

**Table 2.** A summary of studies on geotechnical properties of hydrocarbon-contaminated soils

**Table 3.** Analytical methods for determination of Total Petroleum Hydrocarbons in soils

**Table 4.** Performance of analytical methods in determination of targeted hydrocarbon compounds in soils

**Table 5.** A summary of types and amounts of hydrocarbon compounds considered in the studies on geotechnical properties of hydrocarbon-contaminated soils

**Table 6.** Geotechnical tests on hydrocarbon-contaminated soils

**Table 7.** Hydrocarbon-induced changes in the microstructure of fine-grained soils

**Table 8.** A summary of maximum dry density and optimum moisture content of hydrocarbon-contaminated soils

**Table 9.** Unconfined compressive strength ( $q_u$ ) of hydrocarbon-contaminated soils

**Table 10.** Effects of weathering and aging process on geotechnical properties of hydrocarbon-contaminated soils

**List of Figures:**

**Fig. 1.** The volumes of different types of hydrocarbon contaminations occurred in the west coast of United States of America (2002-2015)

**Fig. 2.** Different kinds of hydrocarbons

**Fig. 3.** SEM images of a particular clayey soil in (a and c) clean, and (b and d) hydrocarbon-contaminated conditions. Reprinted from (Izdebska-Mucha and Trzeciński 2008) with permission from The Publishing Department of Lithuanian Academy of Sciences

**Fig. 4.** SEM images of (a) clean dry pure kaolinite, (b) clean wet pure kaolinite (12 wt.% of water) (c) gas oil-contaminated dry pure kaolinite (12 wt.% of gas oil) (d) gas oil-contaminated wet pure kaolinite (12 wt.% of gas oil and 12 wt.% of water). Reprinted from (Khosravi et al. 2013) with permission from Elsevier

**Fig. 5.** SEM images of (a) clean and (b) hydrocarbon-contaminated Firoozkooh sand

**Fig. 6.** SEM images of Firoozkooh sand: (a) clean, and contaminated by (b) 4 wt.%, (C) 8 wt.%, (d) 12 wt.% of light crude oil

**Fig. 7.** Effects of hydrocarbon contaminations on (a) liquid limit (LL) and (b) Plasticity Index (PI) of fine-grained soils

**Fig. 8.** Effects of hydrocarbon contaminations on coefficient of permeability

**Fig. 9.** Hydrocarbon-induced changes in compression index ( $C_c$ ) of soils

**Fig. 10.** Influences of hydrocarbon contaminations on (a) angle of internal friction, and (b) cohesion of soils

**Fig. 11.** Influences of hydrocarbon contaminations on  $G_{max}$  of sand

**Table 1.** The largest hydrocarbon contaminations in history since 1900

Location	Amount (Tones)	Date	Spill Type	Cause(s)
Kern County, California, United States	1,227,600	1909	Oil Spill	Wellhead blowout
Persian Gulf (Kuwait)	1,091,405	1991	Oil Spill	War
Gulf of Mexico	470,779	2010	Crude oil	Wellhead blowout
Gulf of Mexico	470,000	1979	Oil Spill	Wellhead blowout
Tobago	287,000	1979	Oil Spill	Collision
Persian Gulf (Iran)	260,000	1983	Crude oil Spill	Collision and bombing
700 nautical miles off Angola coast	260,000	1991	Iranian heavy crude oil	Fire / Explosion
Saldanha Bay South Africa	252,000	1983	Light crude oil	Fire
Brittany, France	223,000	1978	Oil Spill	Collision
Gulf of Mexico	162,337	2010	Crude oil	Wellhead blowout
Mediterranean Sea near Genoa, Italy	144,000	1991	Crude oil	Explosion
800 km southeast of Tripoli, Libya	142,860	1980	Crude oil	Wellhead blowout
700 nautical miles off Nova Scotia Canada	132,000	1988	Crude oil	Heavy weather / Fire
Isles of Scilly, England	119,000	1967	Kuwait crude oil	Navigational error
Gulf of Oman	115,000	1972	Crude oil	Collision
North Sea, Belgium	107,140	1971	Oil Spill	Unknown
Shuaiba, Kuwait	106,120	1981	Storage tank	Unknown
Usinsk in Northern Russia (Komi Republic)	104,420	1994	Oil Spill	Ruptured pipeline, old equipment
La Coruña, Spain	100,000	1976	Oil Spill	Collision
Navarino Bay Greece	100,000	1980	Iraqi crude oil	Fire / Explosion

**Table 2.** A summary of studies on geotechnical properties of hydrocarbon-contaminated soils

Ref.	Soil	Hydrocarbon Contaminant(s)	Geotechnical Tests
(Ola 1991)	Silty sand	Bitumen	Compaction, Consolidation
(Evgin and Das 1992)	Quartz sand	Motor oil	Triaxial test
(Tuncan and Pamukcu 1992)	Marine sediments	Crude oil	Atterberg limits, Consolidation, Permeability, Vane shear test
(Cook et al. 1992)	Sand	Crude oil	Compaction, Consolidation, Direct shear test
(Puri et al. 1994)	Sand	Crude oil	Compaction, Consolidation, Direct shear test
(Meegoda and Ratnaweera 1994)	Kaolin-Bentonite	Glycerol, 1-propanol	Consolidation
(Hasan A. Al-Sanad 1995)	Jahra Sand	Benzene, AI-Ritga heavy crude oil, Rawdatain light crude oil, AI-Zoor gas oil	CBR, Compaction, Consolidation Direct shear test, Permeability, Triaxial test
(Al-Sanad and Ismael 1997)			Consolidation, Direct shear test Triaxial test
(Silvestri et al. 1997)	Natural silty clay, Kaolinite clayey silt	Motor oil	Atterberg limits, Compaction, Permeability
(Srivastava and Pandey 1998)	alluvial soils, Sand	Indian crude oil (Servo oil)	Compaction, Permeability, PSD
(Aiban 1998)	Eastern Saudi sand	Heavy crude oil, Medium crude oil	CBR, Consolidation, Triaxial test
(Shin et al. 1999)	Jumoonjin sand	Oman crude oil	Bearing capacity, Direct shear test
(Puri 2000)	Poorly-graded sand	Crude oil	Compaction, Consolidation Direct shear test, Permeability
(Shin and Das 2001)	Jumoonjin sand	Oman crude oil, Oman engine oil, Oman lamp oil,	Bearing capacity, Direct shear test
(Shin et al. 2002)			Compaction, Direct shear test, Permeability
(Khomehchiyan et al. 2007)	Silty sand, Poorly-graded sand, Lean clay	Paraffinic crude oil	Atterberg limits, Direct shear test, UCS, Compaction, permeability
(Singh et al. 2008)	Natural Low plastic clay, Artificial High plastic clay	Used engine oil (U.E.O.), Diesel, Gasoline, Kerosene	Consolidation,
(Singh et al. 2009)	Low plastic clay, High plastic clay, Sand	Used motor oil (U.M.O)	Compaction, Consolidation, Free swelling
(Jia et al. 2010)	Silty soil	Crude oil	Atterberg limits, Compaction, PSD, Direct shear test, SPT
(Rahman et al. 2010)	Sandy loam, Silty loam	Crude oil	Atterberg limits, Compaction Permeability, UCS
(Di Matteo et al. 2011)	Kaolinitic Clay	Ethanol-gasoline	Consolidation,
(Nazir 2011)	High plastic clay	Motor oil	Atterberg limits, Consolidation PSD, UCS
(Kermani and Ebadi 2012)	Low plastic clay	Crude oil	Atterberg limits, Compaction Consolidation, Direct shear test
(Nasr 2013)	Poorly-graded sand	Heavy motor oil, Light gas oil	Direct shear test
(Walia et al. 2013)	CL-ML	Diesel	Atterberg limits, CBR Compaction, Free swelling, UCS
(Khosravi et al. 2013)	Pure kaolinite	Gas oil	Atterberg limits, Consolidation Direct shear test, UCS
(Oyegbile and Ayininuola 2013)	A well graded lateritic soil	Crude oil	Atterberg limits, Compaction Triaxial test
(Alhassan and Fagge 2013)	Poorly-graded sand, Inorganic dark silty clay, Reddish lateritic soil	Crude oil, Low point pour fuel oil (LPFO), Vacuum gas oil	Atterberg limits, CBR, Compaction, Consolidation UCS
(Talukdar and Saikia 2013)	Low plastic clay, High plastic clay, Intermediate plastic clay, clay-sand	Crude oil	Atterberg limits, Compaction, Consolidation, PSD

(Ling and Yong 2013)	Well-graded sand	Palm biodiesel	Direct shear test
(Ijimdiya 2013)	Low plastic clay	Waste motor oil	Compaction, Consolidation, PSD, UCS
(Francis 2013)	A mixture of clay and silt	Crude oil	Bearing capacity test
(Akinwumi et al. 2014a)	Sandy lean clay	Nigerian crude oil	Atterberg limits, CBR, Compaction, Permeability
(Pusadkar and Bharambe 2014)	Black Cotton soil	Petrol and diesel	Atterberg limits, CBR, Compaction
(Siang et al. 2014)	Well-graded sand Gap-graded sand	Palm and engine oil	Direct shear test, Permeability
(Ochepo and Joseph 2014)	Low plastic clay	Spent oil	Compaction, UCS
(Naeini and Shojaedin 2014)	Firoozkooh sand (No. 161)	Crude oil	Triaxial test
(Akinwumi et al. 2014b)	Low plastic clay	Waste Engine Oil	Atterberg limits, CBR, Compaction, Permeability
(Ukpong and Umoh 2015)	Silty sand	Crude oil	Atterberg limits, CBR Compaction, PSD
(Solly et al. 2015)	Clayey sand	Diesel	Atterberg limits, CBR Compaction, UCS
(Onyelowe 2015)	Clayey sand	Pure crude oil	Atterberg limits, CBR Compaction, Consolidation Direct shear test, PSD



**Table 3.** Analytical methods for determination of Total Petroleum Hydrocarbons in soils

Analytical methods for determination of Total Petroleum Hydrocarbons in Soil		
Field methods (in-situ methods)		Laboratory Methods
Common (non-specific) methods	Specific methods	
<ul style="list-style-type: none"> <li>- Gas Chromatography with Flame Ionization (GC-FID),</li> <li>- Gas Chromatography with Photo-ionization Detection (GC-PID),</li> <li>- Gravimetric Determination, Infrared Spectrophotometry (IR),</li> <li>- Turbidimetry Ultraviolet,</li> <li>- Fluorescence Spectroscopic methods,</li> <li>- Thin-layer Chromatography (TLC),</li> <li>- High Performance Liquid Chromatography (HPLC),</li> <li>- Size-exclusion Chromatography, Supercritical Fluid Chromatography (SFC),</li> <li>- Total Organic Carbon,</li> <li>- Isotope Ratio Mass Spectrometry,</li> <li>- Fiber Optic IR Sensor,</li> </ul>	<ul style="list-style-type: none"> <li>- Nuclear Magnetic Resonance (NMR),</li> <li>- Isotope Dilution Mass Spectrometry (IDMS),</li> <li>- Field Portable Gas Chromatography Mass Spectrometry (GC-MS),</li> <li>- Electrospray Ionization Mass Spectrometry (ESI-MS),</li> <li>- High Performance Liquid Chromatography Mass Spectrometry (HPLC-MS),</li> </ul>	<ul style="list-style-type: none"> <li>- General Gravimetry,</li> <li>- Infrared (IR) Spectroscopy,</li> <li>- Gas Chromatography Flame Ionization Detection (GC-FID)*,</li> <li>- Lab-Based Gas Chromatography Mass Spectrometry (GC-MS)*</li> </ul>
<p>* Gas Chromatography Flame Ionization Detection (GC-FID) and Gas Chromatography Mass Spectrometry (GC-MS) can be used in both field and lab.</p>		

**Table 4.** Performance of analytical methods in determination of targeted hydrocarbon compounds in soils

Analytical methods	Targeted hydrocarbon compounds in soils	
	Total Petroleum Hydrocarbons (TPH)	Polycyclic Aromatic Hydrocarbons (PAHs)
General Gravimetry	✓	NA
Immunoassay	✓	✓
Gas Chromatography Flame Ionization Detection (GC-FID)	✓	NA
Gas Chromatography Mass Spectrometry (GC-MS)	✓	✓
Fluorescence Spectroscopy	✓	✓
Raman Spectroscopy	✓	✓
Infrared Spectroscopy	✓	✓
Visible and near-infrared Spectroscopy	✓	✓

**Table 5.** A summary of types and amounts of hydrocarbon compounds considered in the studies on geotechnical properties of hydrocarbon-contaminated soils

Hydrocarbon	Ref.	Hydrocarbon name (if applicable)	Amount (wt. %)
Crude oil	(Tuncan and Pamukcu 1992)	Philadelphia Crude oil	5,10,15
	(Puri et al. 1994)	Not specified	9.5,19,28.5
	(Al-Sanad et al. 1995)	Al-Ritga (H) & Rawdatain (L) crude oil (Kuwait)	2.4,6
	(Al-Sanad and Ismael 1997)	Al-Ritga (H) & Rawdatain (L) crude oil (Kuwait)	2.4,6
	(Srivastava and Pandey 1998)	Servo oil	3.6,9,12
	(Aiban 1998)	Heavy and medium crude oil	2.4,6
	(Shin et al. 1999)	Oman crude oil	1.3,3.8,4.2
	(Puri 2000)	Not specified	9.5,19,28.5
	(Shin and Das 2000)	Oman crude oil	2.4,6
	(Shin and Das 2001)	Oman crude oil	2.4,6
	(Ogboghodo et al. 2004)	Forcados & Escravos light crude oil (Nigeria)	0.5-40 mL.kg <sup>-1</sup>
	(Khamchichyan et al. 2007)	Iranian light crude oil (Paraffinic)	4.8,12,16
	(Kermani and Ebadi 2012)	Iranian light crude oil (Tehran oil refinery)	4.8,12
	(Oyegbile and Ayinoluola 2013)	Not specified	10
	(Alhassan and Fagge 2013)	Not specified	2.4,6
	(Talukdar and Saikia 2013)	Not specified	3.6,9
	(Francis 2013)	Nigerian crude oil (Bonny Light)	5,10,15,20
	(Akinwumi et al. 2014a)	Nigerian crude oil	2.4,6,8,10
	(Naeini and Shojaedin 2014)	Iranian light crude oil (Tehran oil refinery)	4.8,12
(Onyelowe 2015)	Not specified	2.4,6	
Motor oil/Engine oil	(Puri et al. 1994)	Commercial grade motor oil (50W30, 10W30, 20W50)	10.54,21.07,31.61
	(Silvestri et al. 1997)	Not specified	4.6,8
	(Puri 2000)	Commercial grade motor oil (50W30, 10W30, 20W50)	10.54,21.07,31.61
	(Shin and Das 2000)	Oman engine oil	2.4,6
	(Shin and Das 2001)	Oman engine oil	2.4,6
	(Singh et al. 2008)	Not specified	3.6,9
	(Singh et al. 2009)	Used engine oil (U.E.O.)	3.6,9
	(Ijimdiya 2013)	Waste motor oil (Oando lubrication workshop)	1.2,3
(Akinwumi et al. 2014b)	Not specified	2.4,6,8,10	
Gasoline	(Al-Sanad et al. 1995)	Al-Zoor	2.4,6
	(Al-Sanad and Ismael 1997)	Al-Zoor	2.4,6
	(Singh et al. 2008)	Not specified	3.6,9
	(Khosravi et al. 2013)	Iranian Gasoline (provided by NIORDC of Iran)	2.6,12,16,20
	(Nasr 2013)	Not specified	1.2,3
(Alhassan and Fagge 2013)	Not specified	2.4,6	
Diesel	(Singh et al. 2008)	Not specified	3.6,9
	(Walia et al. 2013)	Not specified	4.8,12
	(Ling and Yong 2013)	Palm biodiesel	3.6,10
	(Pusadkar and Bharambe 2014)	Not specified	3.6,9
	(Solly et al. 2015)	Not specified	4, 8, 12
Others	(Ola 1991)	Bitumen	3-5
	(Al-Sanad et al. 1995)	Benzene	2.4,6
	(Al-Sanad and Ismael 1997)	Benzene	2.4,6
	(Singh et al. 2008)	Not specified	3.6,9

**Table 6.** Geotechnical tests on hydrocarbon-contaminated soils

Ref.	Geotechnical tests on hydrocarbon-contaminated soil								
	PSD	Atterberg Limits	Permeability	Compaction	Consolidation	UCS	Triaxial test	Direct shear test	CBR
(Tuncan and Pamukcu 1992)			✓		✓				
(Cook et al. 1992)			✓					✓	
(Evgin and Das 1992)							✓		
(Puri et al. 1994)			✓	✓				✓	
(Meegoda and Ratnaweera 1994)					✓				
(Al-Sanad et al. 1995)	✓		✓	✓	✓		✓	✓	✓
(Al-Sanad and Ismael 1997)					✓		✓	✓	
(Silvestri et al. 1997)	✓		✓	✓					
(Srivastava and Pandey 1998)	✓	✓		✓	✓		✓		
(Aiban 1998)					✓		✓		✓
(Shin et al. 1999)								✓	
(Puri 2000)			✓	✓		✓		✓	
(Shin and Das 2000)			✓	✓				✓	
(Khamsehchiyan et al. 2007)		✓	✓	✓		✓		✓	
(Singh et al. 2008)					✓				
(Singh et al. 2009)			✓	✓					
(Jia et al. 2010)	✓	✓		✓				✓	
(Rahman et al. 2010)		✓	✓	✓				✓	
(Di Matteo et al. 2011)		✓			✓				
(Nazir 2011)		✓			✓	✓			
(Kermani and Ebadi 2012)		✓		✓	✓			✓	
(Nasr 2013)								✓	
(Walia et al. 2013)		✓		✓		✓			
(Khosravi et al. 2013)	✓	✓			✓	✓		✓	
(Oyegbile and Ayininuola 2013)		✓		✓			✓		
(Alhassan and Fagge 2013)		✓		✓	✓		✓		✓
(Talukdar and Saikia 2013)			✓		✓				
(Ling and Yong 2013)								✓	
(Ijimdiya 2013)	✓				✓	✓			
(Akinwumi et al. 2014a)		✓	✓	✓					✓
(Akinwumi et al. 2014b)		✓	✓	✓					✓
(Pusadkar and Bharambe 2014)		✓		✓					✓
(Siang et al. 2014)			✓					✓	
(Ochepo and Joseph 2014)				✓		✓			✓
(Naeini and Shojaedin 2014)							✓		
(Ukpong and Umoh 2015)	✓	✓		✓					✓
(Solly et al. 2015)		✓		✓		✓			✓
(Onyelowe 2015)	✓	✓		✓	✓			✓	✓

**Table. 7.** Hydrocarbon-induced changes in the microstructure of fine-grained soils

Qualitative parameters of microstructure of fine-grained soils	Hydrocarbon-induced changes in microstructure	
	Clean fine-grained soils	Hydrocarbon-contaminated fine-grained soils
Particle surface	- Unchanged	- Hydrocarbon-coated particles
Inter-particle properties	<ul style="list-style-type: none"> <li>- Hydrophilic surface of particles,</li> <li>- No induced adhesion,</li> <li>- Clay-normal electric charged double layer,</li> <li>- Long-range electrostatic repulsive forces among particles,</li> </ul>	<ul style="list-style-type: none"> <li>- Hydrophobic surface of hydrocarbon-coated particles,</li> <li>- Hydrocarbon-induced adhesion among particles,</li> <li>- Lower electric charge among double layers of coated particles,</li> <li>- Short- range (<math>\leq 8</math> nm of separation distance between particles) electrostatic repulsive forces among particles with lower values compared with clean fine-grained soils,</li> <li>- Attractive forces among hydrocarbon-coated layers of particles (in <math>\geq 8</math> nm of separation distance between particles),</li> </ul>
Fabric	<ul style="list-style-type: none"> <li>- Dispersed fabric,</li> <li>- Face-to-Face (FF) contacts among particles,</li> <li>- Edge-to-Edge (EE) contacts among particles,</li> <li>- An oriented fabric,</li> <li>- Smaller pores,</li> </ul>	<ul style="list-style-type: none"> <li>- Flocculated fabric,</li> <li>- Edge-to-Face (EF) contacts among particles more usual,</li> <li>- lesser smaller pores compared with clean fine-grained soils,</li> <li>- Less oriented fabric,</li> <li>- decomposed aggregates</li> </ul>

**Table 8.** A summary of maximum dry density and optimum moisture content of hydrocarbon-contaminated soils

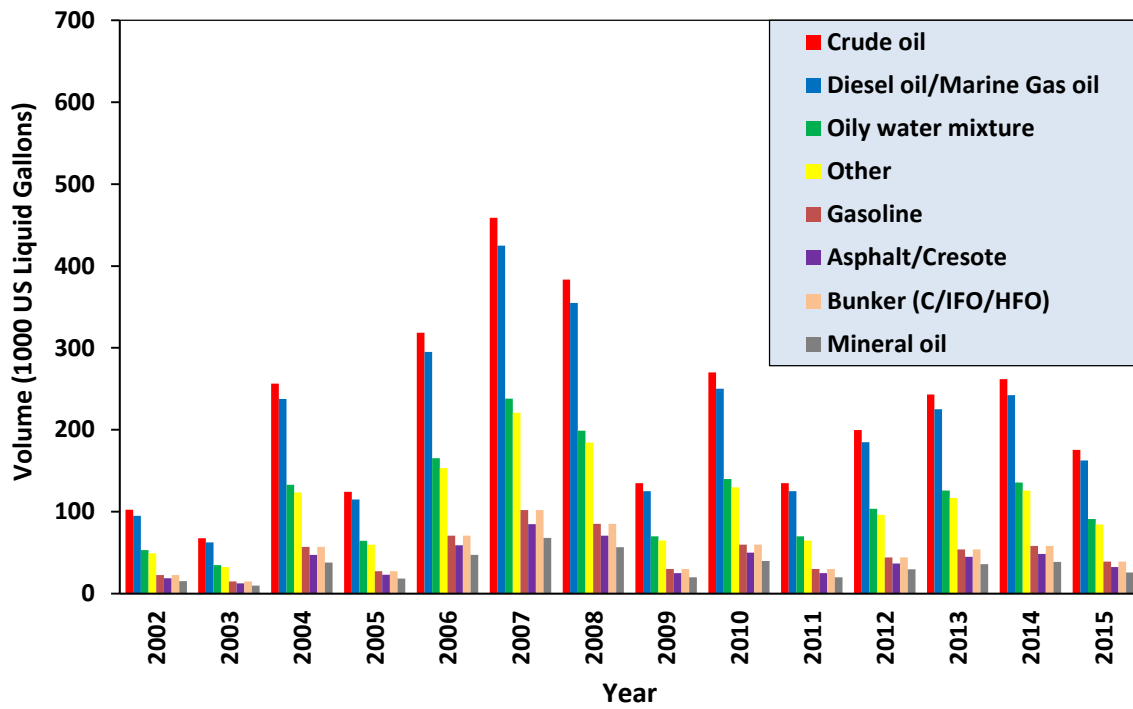
Ref.	Soil type	Hydrocarbon type	Clean sample		Hydrocarbon content (wt.%) in contaminated samples																	
					2		3		4		6		8		9		10		12		16	
			OMC (%)	MDD (kg/m <sup>3</sup> )	OMC (%)	MDD (kg/m <sup>3</sup> )	OMC (%)	MDD (kg/m <sup>3</sup> )	OMC (%)	MDD (kg/m <sup>3</sup> )	OMC (%)	MDD (kg/m <sup>3</sup> )	OMC (%)	MDD (kg/m <sup>3</sup> )	OMC (%)	MDD (kg/m <sup>3</sup> )	OMC (%)	MDD (kg/m <sup>3</sup> )	OMC (%)	MDD (kg/m <sup>3</sup> )	OMC (%)	MDD (kg/m <sup>3</sup> )
(Al-Sanad et al. 1995)	Sand	Heavy crude oil	12	1890	7.5	1940			7	1930	2	1825										
(Silvestri et al. 1997)	Kaolinite Natural Clay	Motor oil Motor oil	27 27	1425 1420	25	1420			23 26	1415 1395	21.5 22.5	1375 1380	22	1375								
(Srivastava and Pandey 1998)	Alluvial soil Sand	Servo oil Servo oil	16 12.7	1840 1745			15.5 15.5	1860 1710			12.6 8.7	1880 1720			11.1 4.7	1865 1665			10.1 2.6	1835 1635		
(Khamsehchiyan et al. 2007)	CL SP SM	Light crude oil Light crude oil Light crude oil	16.4 14.4 13.2	1864 1900 1828					13.8 10 9.6	1852 1872 1830			9.5 8.4 7.2	1832 1844 1820					7.2 5.6 5.5	1800 1840 1818	3.2 2.0 2.8	1812 1824 1812
(Singh et al. 2009)	CL CH	Used motor oil Used motor oil	14.9 19.5	1815 1560			15.5 21.6	1785 1532			16.2 21.7	1726 1510			16.8 23.3	1677 1501						
(Rahman et al. 2010)	Sandy loam Silty loam	Crude oil Crude oil	23 23.5	1670 1600					21.4 22.5	1570 1580			20 22	1550 1560					18.5 20	1530 1550	17.5 16.5	1500 1550
(Kermani and Ebadi 2012)	Silty soil	Light crude oil	21	1640					16	1690			13.5	1695					11	1725		
(Walia et al. 2013)	CL-ML	Diesel	10.3	1765					9.06	1697			8.75	1667			8.00	1648				
(Akinwumi et al. 2014a)	CL	Nigerian crude oil	15.3	1822	15.1	1810			14.8	1805	14.7	1803	14.6	1792			14.6	1785				
(Akinwumi et al. 2014b)	CL	Engine oil	15.4	1822	13.60	1820			12.4	1817	10.7	1810	9.3	1806			7.8	1795				
(Pusadkar and Bharambe 2014)	Black Cotton	Petrol Diesel	15.89 15.89	1291 1291			14.52 14.32	1131 1211			14.32 14.12	10.07 10.51			14.22 13.93	8.75 9.70						
(Onyelowe 2015)	Clayey sand	Crude oil	16.2	1900	12.2	1935			13	1900	13.8	1900										

**Table. 9.** Unconfined compressive strength ( $q_u$ ) of hydrocarbon-contaminated soils

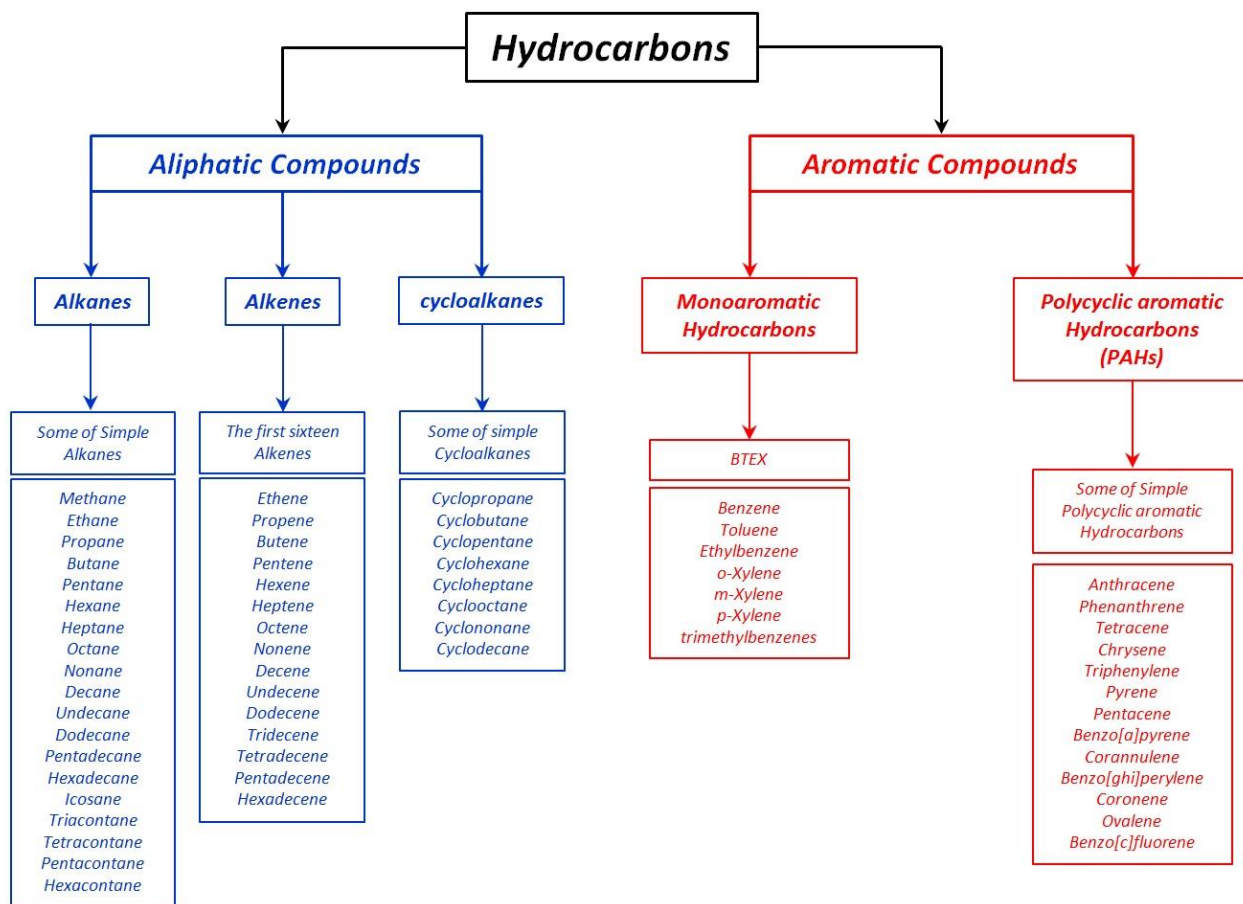
Ref.	Soil type	Hydrocarbon type	Clean sample		Hydrocarbon content (wt.%) in contaminated samples													
					2		4		6		8		12		14		16	
			$\epsilon_q$ (%)	$q_u$ (kPa)	$\epsilon_q$ (%)	$q_u$ (kPa)	$\epsilon_q$ (%)	$q_u$ (kPa)	$\epsilon_q$ (%)	$q_u$ (kPa)	$\epsilon_q$ (%)	$q_u$ (kPa)	$\epsilon_q$ (%)	$q_u$ (kPa)	$\epsilon_q$ (%)	$q_u$ (kPa)	$\epsilon_q$ (%)	$q_u$ (kPa)
(Khomehchiyan et al. 2007)	CL SM	Light crude oil Light crude oil	4.40 2.90	36 9.4			5.20 1.90	40 8.8			4.00 1.80	22 6.6	3.60 2.60	16 5.8			7.60 2.80	8.0 3.6
(Walia et al. 2013)	CL-ML	Diesel	100	140			155	90			160	65	150	35				
(Khosravi et al. 2013)	Pure kaolinite	Gas oil			1.2	12	0.95	12.5	0.82	14			0.9	20	1.1	17.5		
(Ijimdiya 2013)	Low plastic clay	Waste motor oil		155		185		180		152		105						
(Solly et al. 2015)	Clayey sand	Diesel		17				18				25		29				



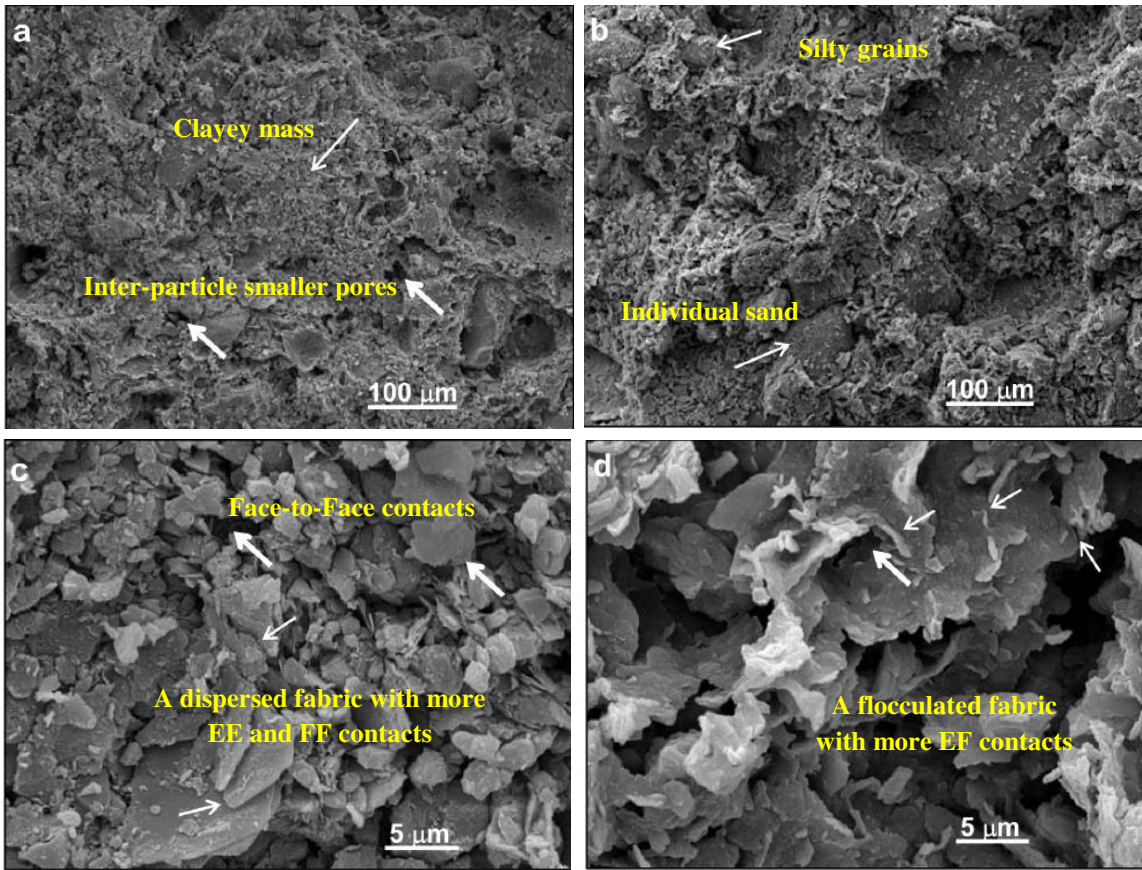




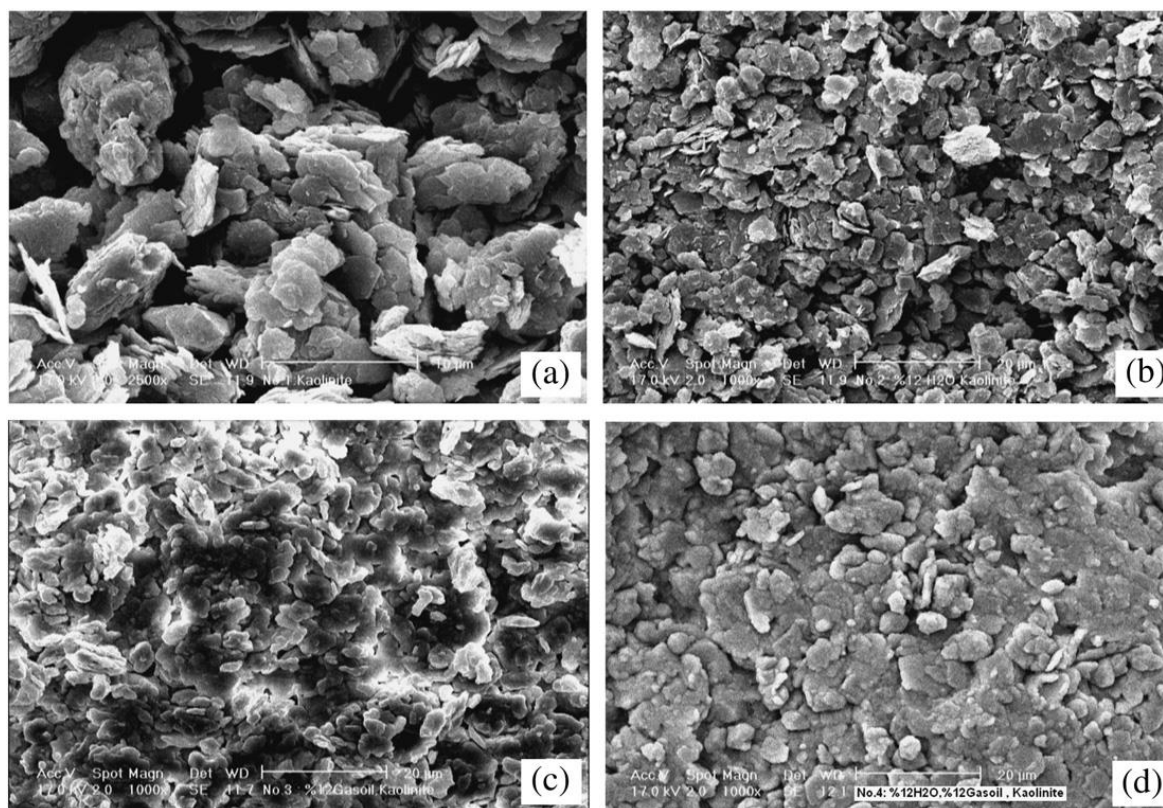
**Fig. 1.** The volumes of different types of hydrocarbon contaminations occurred in the west coast of United States of America (2002-2015)



**Fig. 2.** Different kinds of hydrocarbons



**Fig. 3.** SEM images of a particular clayey soil in (a and c) clean, and (b and d) hydrocarbon-contaminated conditions. Reprinted from (Izdebska-Mucha and Trzciński 2008) with permission from The Publishing Department of Lithuanian Academy of Sciences

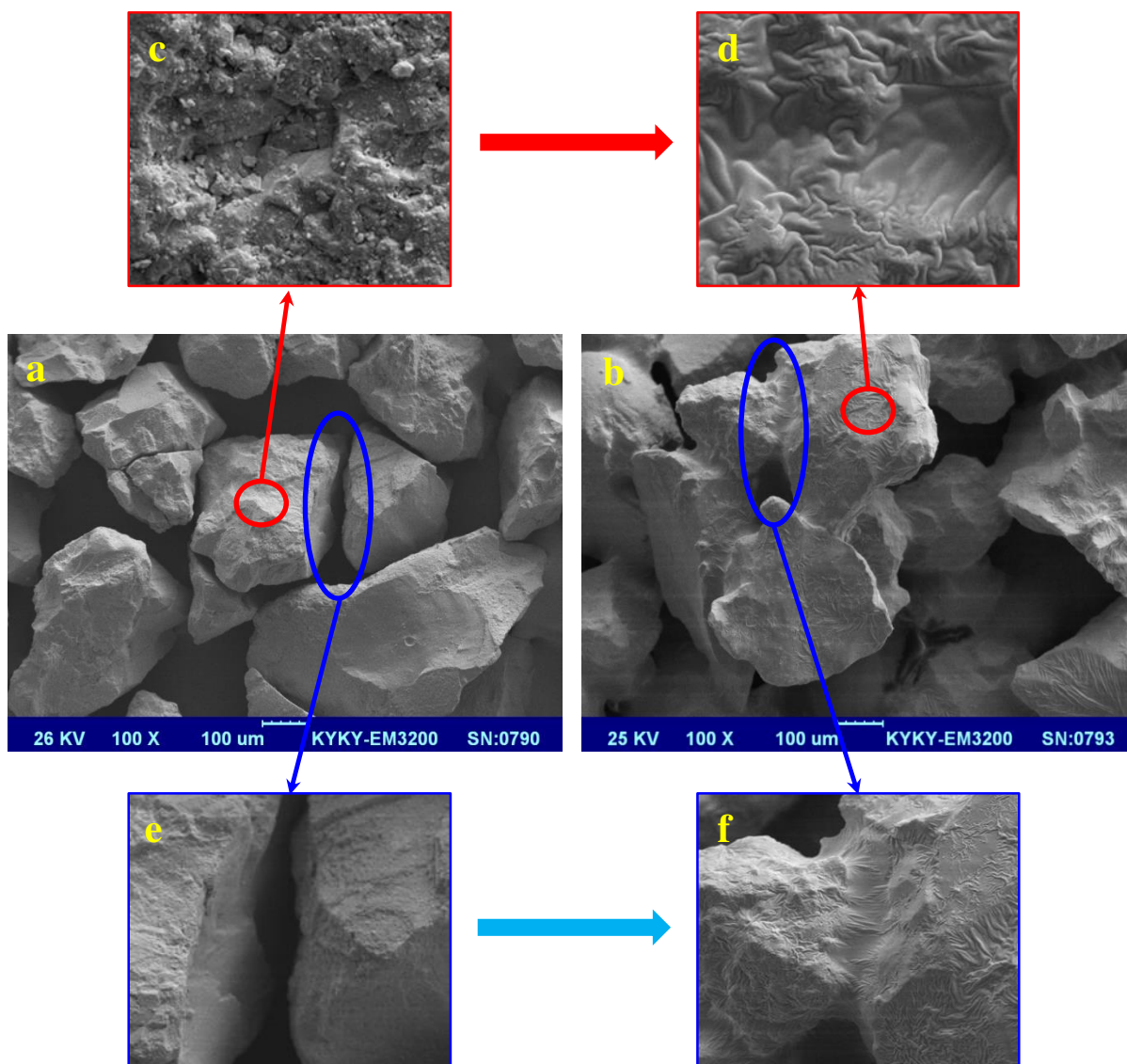


**Fig. 4.** SEM images of (a) clean dry pure kaolinite, (b) clean wet pure

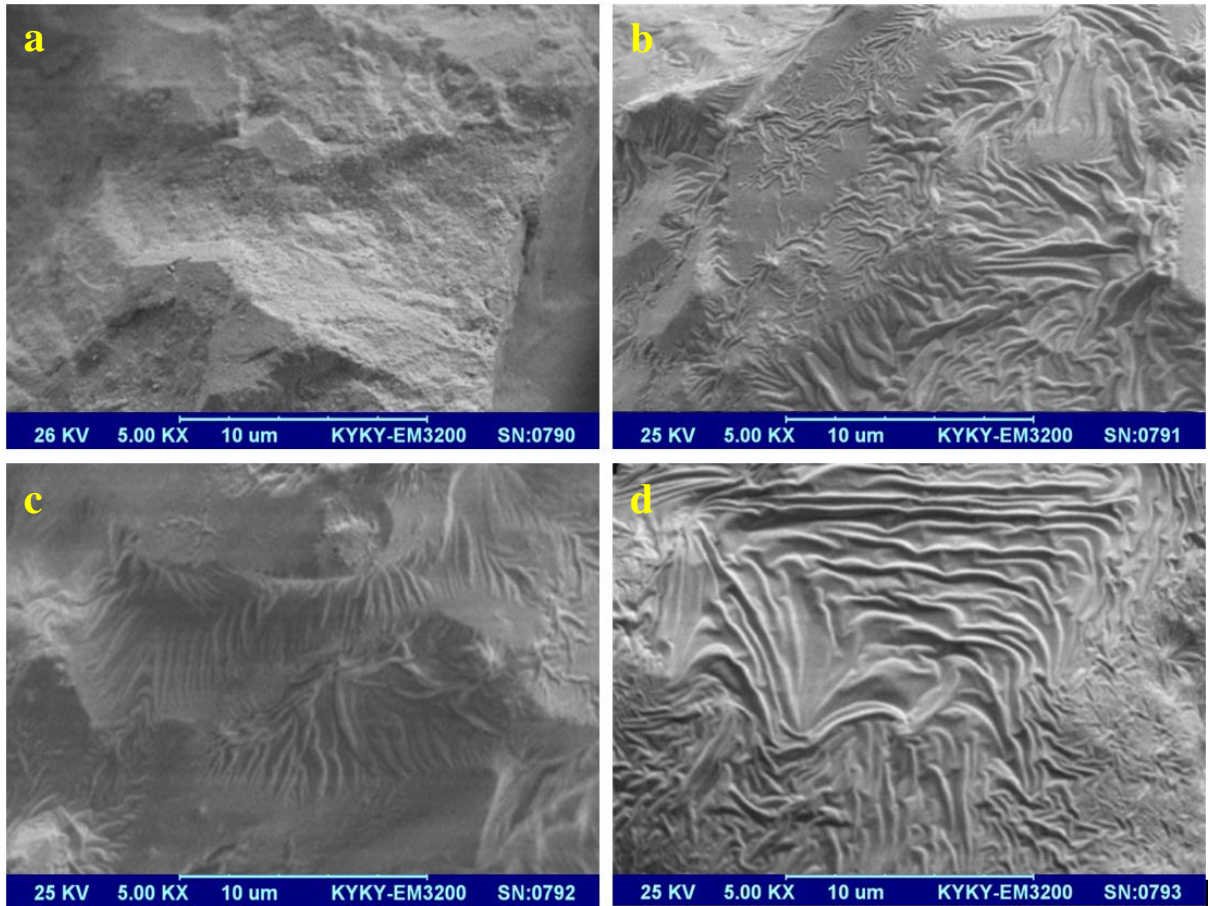
kaolinite (12 wt.% of water) (c) gas oil-contaminated dry pure kaolinite (12 wt.% of gas oil)

(d) gas oil-contaminated wet pure kaolinite (12 wt.% of gas oil and 12 wt.% of water).

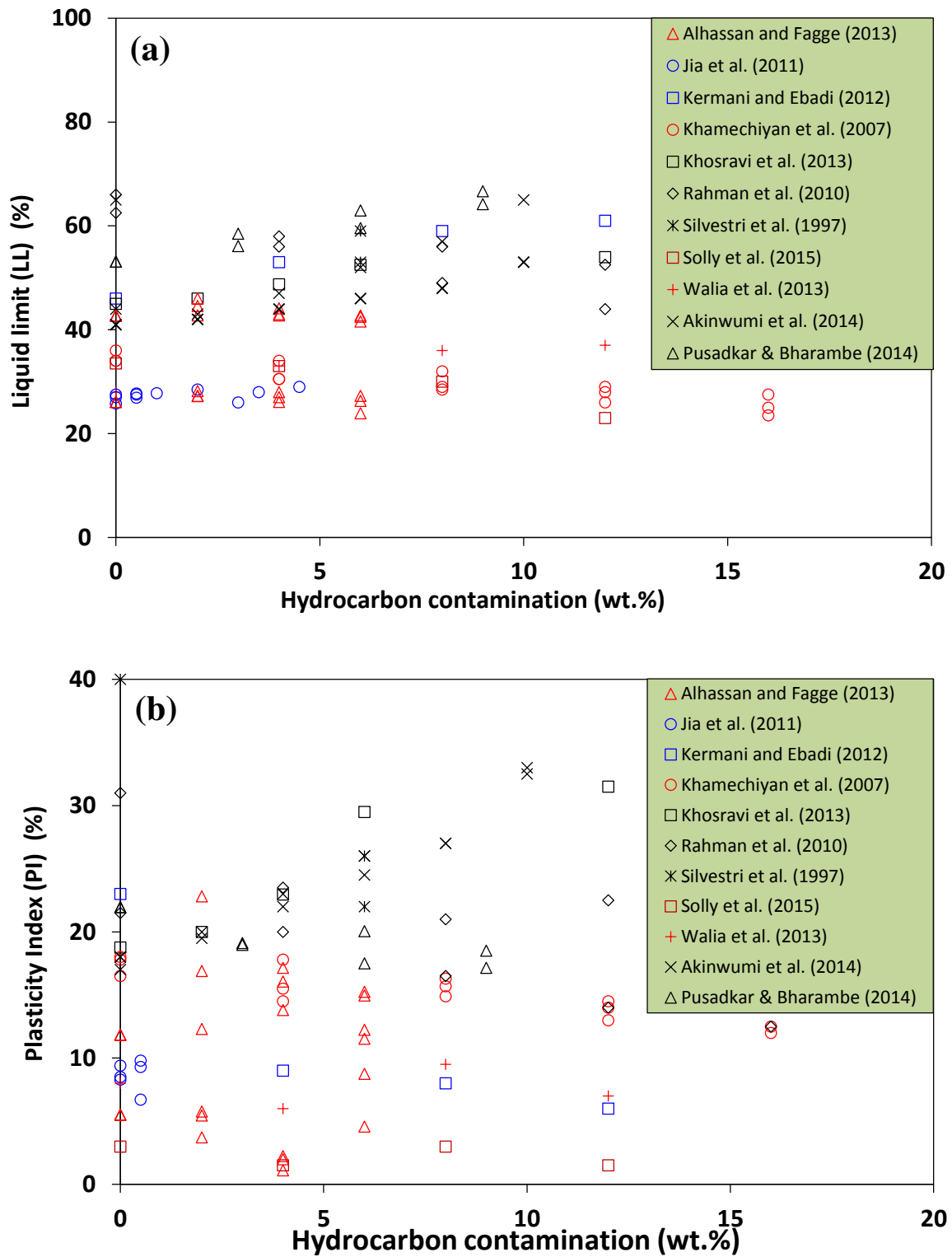
Reprinted from (Khosravi et al. 2013) with permission from Elsevier



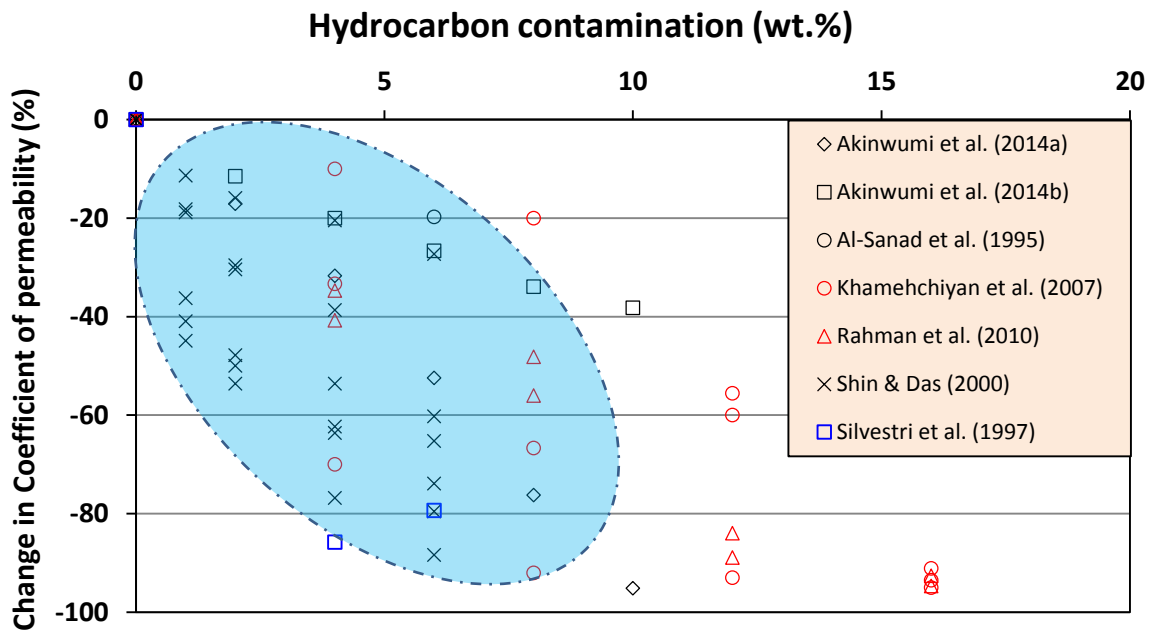
**Fig. 5.** SEM images of (a) clean and (b) hydrocarbon-contaminated Firoozkooch sand  
(provided by the authors)



**Fig. 6.** SEM images of Firoozkooch sand: (a) clean, and contaminated by (b) 4 wt.%, (C) 8 wt.%, (d) 12 wt.% of light crude oil (provided by the authors)



**Fig. 7.** Effects of hydrocarbon contaminations on (a) liquid limit (LL) and (b) Plasticity Index (PI) of fine-grained soils



**Fig. 8.** Effects of hydrocarbon contaminations on coefficient of permeability



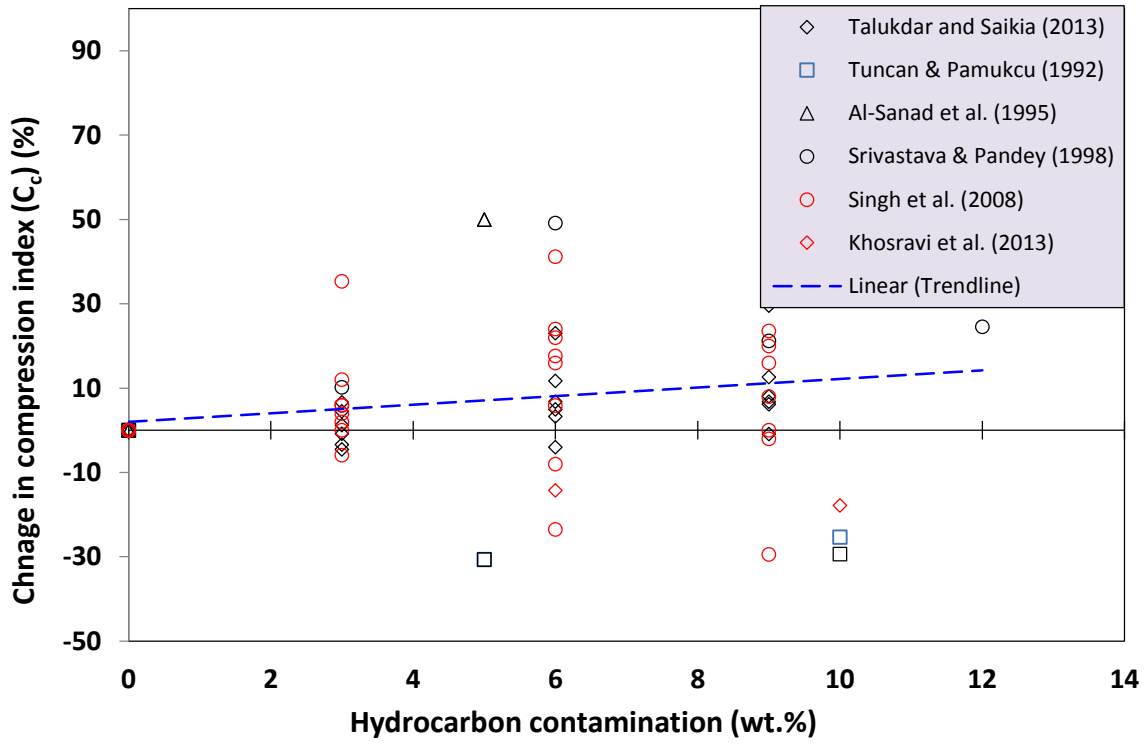
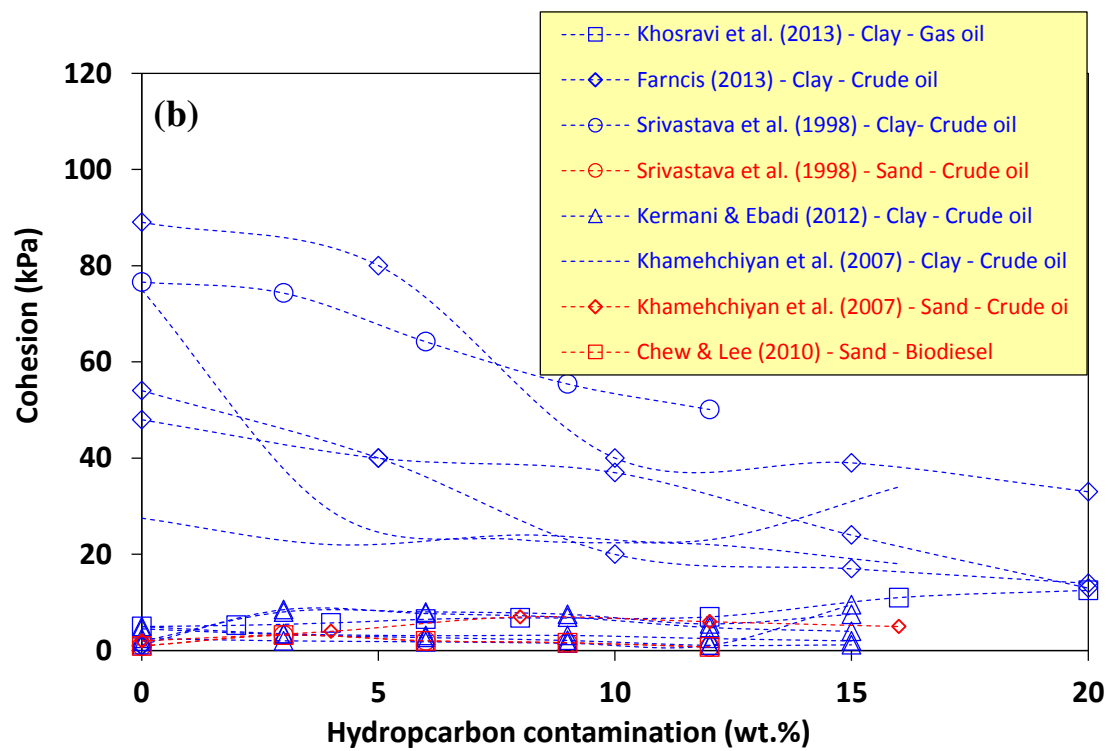
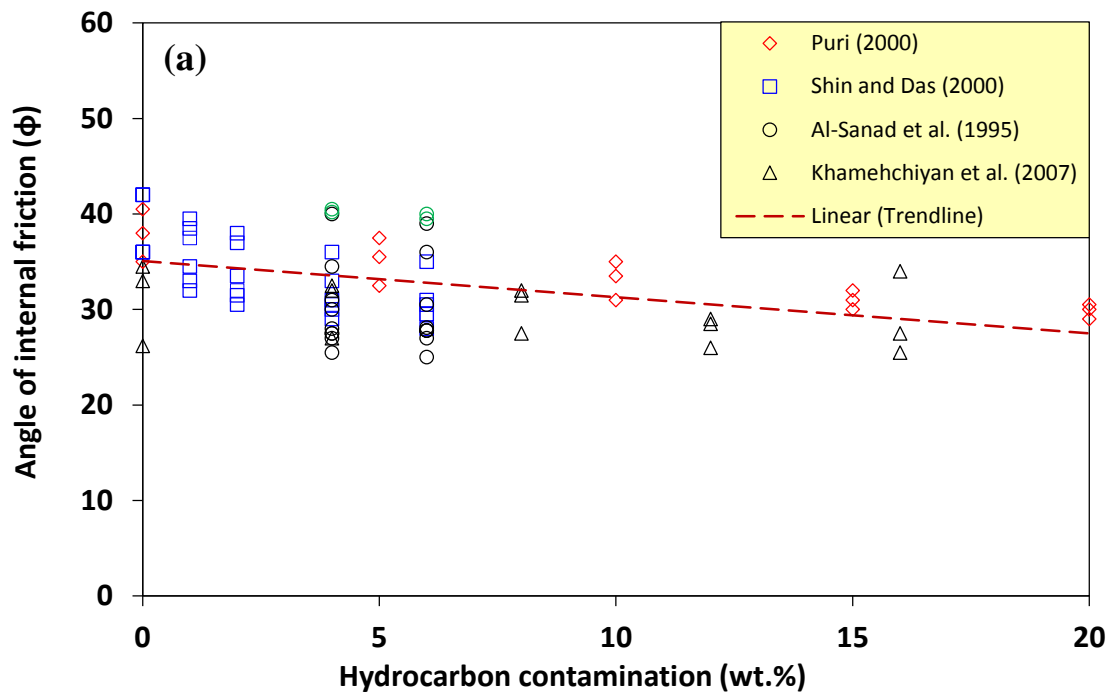


Fig. 9. Hydrocarbon-induced changes in compression index (C<sub>c</sub>) of soils



**Fig. 10.** Influences of hydrocarbon contaminations on (a) angle of internal friction, and (b) cohesion of soils

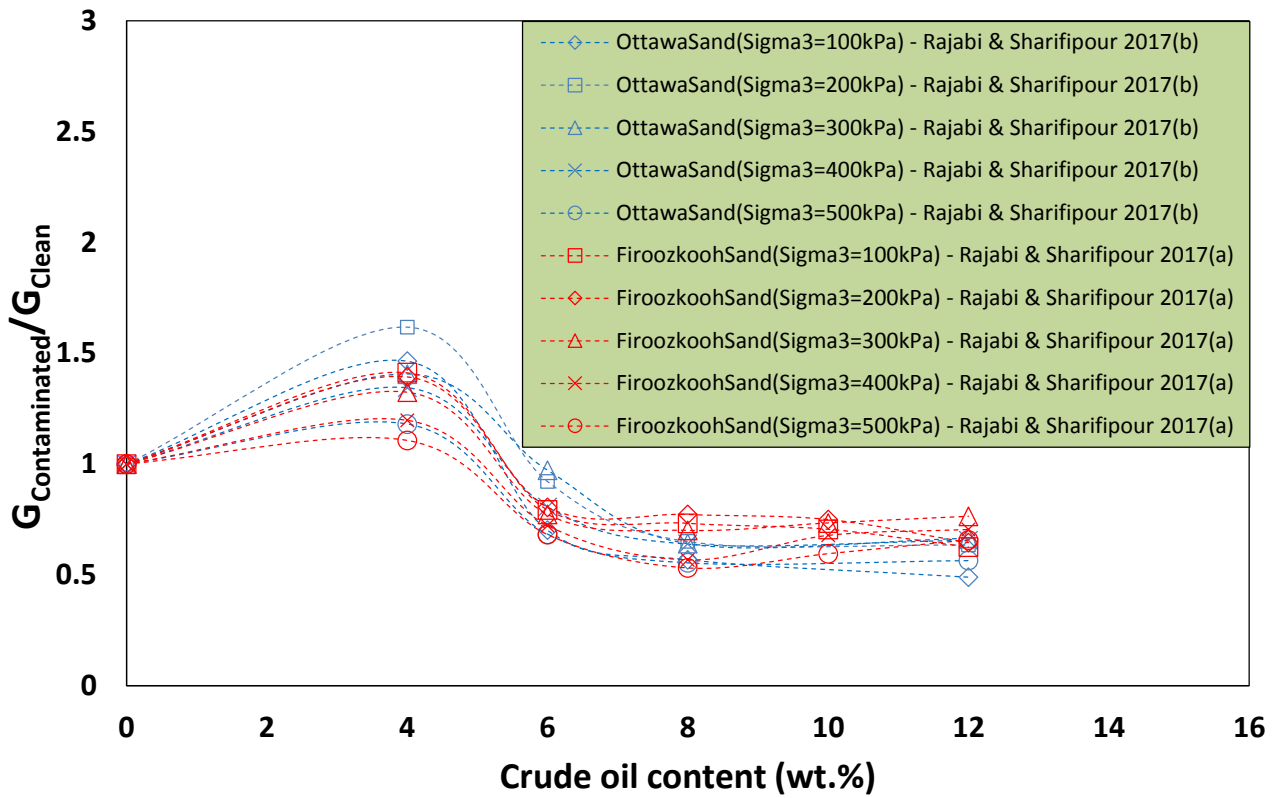


Fig. 11. Influences of hydrocarbon contaminations on  $G_{\text{max}}$  of sand