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Physical modeling of the mechanical behavior of crude oil contaminated mixed soils based on Mini-Cone data

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ABSTRACT: It has been a long time since crude oil products and, their derivatives have contaminated soil. Crude oil contamination is an unavoidable consequence of rapid overpopulation and, the industrialization process. Crude oil contamination can change soil geotechnical behavior and, affect soil strength, foundation-bearing capacity, and slope stability. On the other hand, "mini-cone' tests have rapidly become the most famous type of on-site testing. Because, the mini cone is a fast and, economical experiment that continuously provides information on the geological layout and, the proper assessment of soil properties. This paper compares the changes in the tip and, side resistance of the mini-cone. There are mixed soils of two types of fine-grained sand with 10%, 20%, 30%, 40%, and 50% kaolinite clay, which were tested with 4% and, 8% crude oil and, different moisture contents. These investigations have been done with the physical modeling method and, calculating the value of Ic, focusing on the mini-con data. Results showed that the tip and, the side resistances of the "mini-cone" were decreased in mixed soils with increasing crude oil content and, changes in moisture contents. Except for two sandy soils mixed with 10% and, 20% clay, which were mixed with 4% crude oil. There was an increase in tip and, side resistance due to the lack of the maximum density in the laboratory chamber compared to the standard Proctor test. Also, with these changes, Ic calculation found that the soil's behavior shifted towards finer soils.

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1- Introduction

Engineers are increasingly required to exercise creative judgment in their design projects due to the growing complexity and, variety of civil projects, as well as the challenges posed by more specialized and, intricate structures, alongside environmental, economic, and, practical constraints. Considering bed material specifications is essential in any design or construction project. The appropriate, safe, stable, and, economical performance of structures is ultimately influenced by the foundation system on the natural bed. Therefore, to ensure satisfactory service, it is crucial to understand the behavior of these materials and, implement improvements to address their natural weaknesses in strength, stiffness, and, hydraulic properties.

It has been a long time since crude oil products and, their derivatives have contaminated soil during the transportation or storing process in discovery and, purification facilities and, transfer ways. Crude oil contamination is an unavoidable consequence of rapid overpopulation and, the industrialization process. Crude oil contamination can change soil Geotechnical behavior and, affect soil strength, foundation-bearing capacity, and slope stability. Therefore, it is vital to investigate the effects of contamination on soil's strength and, behavior. Scholars have researched changing the parameters and, soil strength due to the presence of crude oil. Examples of researchers who have contributed to this field include Ewetola et al. [1], Zulfahmi Ali Rahman et al. [2], Hasan A. AI-Sanad et al. [3], Eun Chul Shin et al. [4], Ukpong, E. et al. [5], Mashalah Khamehchiyan et al. [6], M. Ahmadi et al. [7], Akinwumi I. I. et al. [8], Z. N. Rasheed et al. [9], Neven Matasovic et al. [10], H. Haeri, et al. [11] and, M. Shahbazi et al. [12].

Mini-cone Tests have rapidly become the most famous type of on-site testing. Because, the mini cone is a fast and, economical experiment that continuously provides information on the geological layout and, the proper assessment of soil properties. These tests have been planned according to ASTM-3441 (mechanic systems) and, ASTM-5778 (electric and, electronic systems). Include transferring steel cylindrical rod into the soil with standard speed and, measuring the tip and, side resistance of the cone.

Many specialists have utilized mini cone data to determine soil behavior classification (SBC) and, soil strength, resulting in the development of numerous graphical representations. Begenmann [13] was a pioneer in defining soil profiles using CPT data. Following his work, numerous researchers have introduced procedures and, graphs for soil behavior

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classification and, the alteration of soil strength parameters. Notable contributions in this field have been made by Schmertmann [14], Douglas and, Olsen [15], Robertson et al. [16], Robertson [17], Jefferies and, Davies [18], Eslami and, Fellenius [19], Makusa *et a*l. [20], O'Kelly [21], Drevininkas [22], Yi [23], Ramaiah and, Ramana [24], Shirani [25], Esmailzade et al [26], and, Esmailzade et al [27].

However, there is a limited number of studies comparing soil behavior differences concerning soil type and, contamination, particularly crude oil. This study examines changes in the behavior of sandy-clay soils by varying clay content, crude oil concentration, and, moisture levels. The investigations were conducted using physical modeling and, focused on calculating the Ic value, emphasizing mini-cone data.

This research investigated five main groups as follows: first, sand mixtures were prepared in equal proportions, to which Kaolinite clay was subsequently added in increments of 10%, 20%, 30%, 40%, and, 50% (by weight). Six different conditions of these mixtures were studied, varying in moisture and, crude oil content (4% and, 8%) across each of the five main soil groups. These conditions were determined based on standard proctor tests, and, all experiments were performed in a controlled chamber using a mini-cone apparatus.

2- Materials, tools, and equipment

2- 1- Materials

In this study, mixtures of two different fine sands and, Kaolinite clay have been used for preparing samples, since the natural soil of Iran's southern refineries is usually a combination of fine sands and, clays.

Two different fine sands from the "Silica Sand MFG" corporation have been used. Their specifications are expressed in the following:

Sand 1: This fine sand with angular particles is usually utilized for casting big steel and, cast iron fragments or preparing sport grass field beds [28]. Figure 1(a) shows the shape and, grading curve, so Tables 1(a) and, 1(b) show the physical specifications and, chemical compounds of this sand, respectively.

Sand 2: Next fine sand is usually used for the production of cast iron fragments in small with high filtration. Figure 1(b) shows the shape and, grading curve, and, so, Tables 1(c) and, 1(d) indicate this sand's physical specification and, chemical compounds, respectively.

According to clay abundance in the southern part of Iran especially Iran's southern refineries, in this project, Kaolinite clay (ZWMK 1) from the "Iran China Clay Industries" company has been utilized. Because of less water absorption, Kaolinite clay has a higher resemblance with silt in relation to other clays. It needs to be mentioned that its less Specific surface area compared to other clays is another reason for its less water absorption. This clay is more practical in tile, glazed, and sanitary Chinese. Figure 1(c) shows the shape and, grading curve, so Table 1(e) indicates chemical analyzation of this clay.

Crude oil is one of the most prevalent geotechnical contaminants, which can cause soil pollution during the discovery procedure, transportation, storing, or even around transport pipes or refineries. Gravity force causes the crude oil penetration to soil and, in the following, contaminating underground water and, altering considerably soil geotechnical parameters. Therefore, the possibility of structure failure will increase, in the projects with oil-polluted beds. There are many purification methods for reusing oil-polluted soil, but due to the widespread of contaminated areas, such as the soils of the refineries around, these solutions cannot be considered economical. So acquiring geotechnical behavior knowledge is essential. In this study, 600-liter crude oil has been supplied from the Tehran refinery (located on Qom road). Table 1(f) describes this material's specs.

2- 2- Tools

Construction, triggering, and calibration of the mini cone was the first priority, because of the test types. On the other hand, the tests required special software for reading sensor data. In the following, different parts of this system will be described. There is the mini cone device with a 3.57 cm diagonal, 13.38 cm rod length of friction sleeve and, 118 cm height, in the lab. According to mentioned sizes, this device has a cross-section of 10 cm^2, and the side surface of friction is 15 cm^2 (Figure 2).

Another essential tool for the simulation of soil environment in both contaminated and, uncontaminated situations is a lab chamber (1g). For simulating tests, a 1g chamber system has been utilized which is a very common tool in the physical models. This device has a bigger aperture size, which makes it usable for constructing other tests like plate loading. It is built out of a cylinder stainless steel tank with 8 mm thickness. The inner surface is polished as much as possible, and, then is colored. Cylinder chamber dimensions are 60 cm diagonal and, 100 cm height. This chamber is designed in two pre-constructed parts, which will be bolted over each other and, stiffed. There is a drain valve located at the bottom for continued washing (Figure 3(a) and, 3(b)).

A hydraulic jack with a 3-phase engine and, 8.6 amp current and, 220 Volt has been used to ease the mini cone-rod penetration. This jack was built at the "Hakim Industry and, Science" Iranian company by the Amirkabir University of Technology order. Figure 4 shows the shape and, the construction dimensions.

2- 3- Equipment

In order to receive the mini cone data, an electronic receiving system (data logger) was needed. This equipment uses inner and, outer sensors for recording time or location data. "Atron" Iranian company device has been utilized in this project. This system has 16 input channels with simultaneous data collecting ability (multi Plax 16 channels) and, a data reserving rate of a maximum of 100 samples in one second in 8-channel mode (Figure 5(a)).

In order to stabilize the penetration rate of the mini cone, a Korean invertor from LG Corporation with "Ig5A" code has been established. It is a device to shift direct current to alternating current. In addition, it has various abilities like selective vector control method V/F, engine parameter automatic regulation, powerful moment at any velocity, and memory with preserving five last errors (Figure 5(b)).

3- Research Methodology

In this research, five main groups were investigated. First, a mixture was prepared of both sands equally. Then the amounts of 10%, 20%, 30%, 40%, and 50% (weight percent) of Kaolinite clay were added to them, respectively. Different states of mixture with moisture and, crude oil (4% and, 8% by weight of the soils) were studied for each of the five main soil groups. These states were determined after obtaining the results of the standard protractor. The use of these different percentages of soils, crude oils, and moistures in this paper is the existence of different states, which exist in the soils of oil-rich areas. Therefore, first, each soil group from the five main groups with optimal moisture was evaluated before crude oil contamination entered them (tests of the first series). In the following, it was assumed that the first 4% and, then 8% of crude oil penetrated into the normal consolidated soil (tests of the second and, third series). Then crude oil replaces a certain amount of water in the soil and, it is consolidated with the optimal moisture content of each of 4% and, 8% of crude oil, over time (experiments of the fourth and, fifth series). Finally, soil behavior was investigated when soils mixed with 4% crude oil were consolidated with the optimal moisture specific to it, under the influence of 4% more water because entering the rainfall or another water (experiments of the sixth series). It should be noted that increasing the liquid (either crude oil or moisture) would cause the creation of a liquid phase and, subsequently pore pressure, which was avoided due to the use of a mini-cone device and, not mini-cones. According to the statement of the problem, none of the soils reached saturation, so the pore pressure was zero.

3- 1- Standard Proctor Test

This is a test to determine samples' dry density and, optimum moisture content according to ASTM 698 for mixed soils, with and, without contamination. The crude oil contents were 4% and, 8% by weight of the soils. Preparation of soil samples must be applied therefore soil with three different contamination rates (0%, 4%, 8%) has been provided and, packed in two layers of plastics before geotechnical tests. These samples then rested for 24 hours away from any light to achieve stability and, better contamination effectiveness (Figure 6(a)). After this process, initial tests have been performed.

3- 2- Samples Preparation

Subgroups were established for each main soil group based on the determined maximum density and, the mixing percentages of soil, crude oil, and, moisture content. Mini-cone tests were then performed. Soil quantities were determined based on the maximum density from the standard proctor test, and were weighed and, placed into a sample chamber. The samples were compacted to a precise height of 5 cm using a wooden bar. During hand compaction (Figure 3(c)), the height was monitored at four points with a meter to ensure uniform and, homogeneous compaction. This process was repeated layer by layer until the soil reached a height of 50 cm. At this point, the upper part of the chamber was bolted onto the lower part, and, the process continued until the soil reached a height of 90 cm. The samples were then left to stabilize for 24 hours in the lab, covered by an isolated plastic bag, to ensure uniform distribution of moisture or crude oil content before testing began (Figure 6(b)).

3- 3- Set up devices

Construction and, completion of the mini cone device started in the summer 2013 and, finished in the autumn 2018. Setting up the system and, data logger, calibration of the device, and providing a hydraulic jack and, inverter to achieve standard speed (20 mm/s) have been planned according to ASTM 3441 (mechanic systems) and, ASTM 5778 (electric and, electronic systems).

The output data of the data logger was based on the time of the dipping of the rod in the chamber, which was measured as the height of the penetration of the rod, due to the fixed speed (20 mm/s) and, it multiplied at the recorded time. Therefore, increasing the tip and, side resistance was obtained based on the depth of penetration of the rod. Assembles of tools and, equipment were done in the "Groundwater, Soil and, HSE Pollution" lab of "Amirkabir University of Technology".

3- 4- I_c[1] calculate

Finally, the normalized cone parameters Q_t and, F_r were calculated. These parameters can be combined into one Soil Behavior Classification (SBC) based on index I_c. Index I_c is the radius of the essentially concentric circles that represent the boundaries between each SBC_n (Normalized mini cone Soil Behavior Classification) chart zone. Profiles of I_c provide a simple guide to the continuous variation of soil behavior type in a given soil profile based on CPT results. I_c can be defined as follows;

$$I_c = \left(\left(3.47 - \log Q_t\right)^2 + \left(\log F_r + 1.22\right)^2 \right)^{0.5} \quad (1)$$

where:

Normalized cone resistance:

$$Q_t = \frac{q_c - \sigma_{v0}}{\sigma'_{v0}} \quad (2)$$

Friction sleeve:

1 Index I_c is the radius of the essentially concentric circles that represent the boundaries between each SBC_n

$$F_r = \frac{f_s}{q_c - \sigma_{v0}} \times 100\% \tag{3}$$

Note:
• Corrected cone resistance:

$$q_c(MPa) = \frac{\text{Mini cone tip resistance}}{10cm^2 (The \text{ cross-sectional area of mini cone rod}} \tag{4}$$

• Sleeve friction resistance:

$$f_s(kPa) = \frac{\text{Mini cone side resistance}}{150cm^2 (The \text{ engagement side area of mini cone rod}} \tag{5}$$

• Soils density (Ɣ) was measured through laboratory experiments.
• The effective stress was considered equal to the total stress since the soils were not saturated $\sigma_{v0} = \sigma'_{v0}$ [29]

4- Results

4- 1- StandardProctor Test Results

The results of the grain size distribution curve tests are shown in Figure 7, and, the standard Proctor test results are presented in Table 2. It should be noted that the curves were obtained only for three sand-clay mixtures containing 10%, 30%, and, 50% clay. By calculating the optimal moisture content and, the maximum density of the soils, both with and, without 4% and, 8% crude oil, the experimental subgroups for each main soil group and, the degree of soil compaction in the laboratory chamber (1 g) were determined.

4- 2- Determining the subgroups of each of the soil main groups, according to the Proctor standard

According to the results of standard Proctor tests, for each of the five main groups of soils, six different conditions were considered as follows.

In the first step, each of the five soil types with the optimum moisture content and, without contamination was tested to determine the maximum strength of the soil in the densest state. In the second and, third steps, to each of the previous steps samples were added 4% and, then 8% crude oil, to obtain the effect of crude oil entering the soils. In the fourth step, each of the main soil groups was mixed with 4% crude oil and, its optimum moisture content (for example: For sand mixed with 10% clay, the optimum moisture content corresponds to 4% of the crude oil was 5% water). In the fifth step, the same operation (the fourth step) was done for the mixture of 8% crude oil and, its optimum moisture content (for example: For sand mixed with 10% clay, the optimum moisture content corresponds to 8% of the oil was 1% water). In the sixth step and, finally, to determine the effect of additional moisture on the mixture of soil and, crude oil, 4% more moisture was added to the mixture of each soil with 4% oil and, its optimum moisture content (soil related to the fourth step).

Therefore, six different states of composition, with and, without contamination and, varying moisture contents, were investigated for each of the five soil groups tested, resulting in a total of thirty different tests. A coding system was used to facilitate the identification of soil groups, which is explained at the bottom of Table 3. Additionally, Table 3 details the order in which each material (moisture and, crude oil) was added to the soils and, provides the corresponding codes.

4- 3- Mini cone data and, I_c graphs

In Figure 8, the diagrams of the mini cone tip and, side are displayed separately for the main groups of soils. In each diagram, six states of each group are clearly defined (different moisture contents and, with and, without contamination). Therefore, there are ten diagrams according to the five main groups, each of which includes tip and, side resistance. On the other hand, in Fig 10, the tip and, side diagram of the mini cone is drawn for all the six states of the main groups (different moisture contents and, with and, without contamination). There are twelve diagrams in this figure due to the existence of five main soil types and, their tip and, side resistance. Finally, I_c diagrams are also drawn in Figure 10 for thirty available modes (five main groups in six different states). Then, the normalized cone parameters Q_t and, F_r was calculated (based on the density (Ɣ) and, total stress (σ_{vo})) and, combined into the Soil Behavior Classification (SBC) index, I_c.

5- Evaluations and, Discussions

According to the results of the mini cone experiments and, index I_c (determining SBC), this is summarized with the percentage of soil resistance changes with regard to the addition of moisture and, crude oil to the soil without contamination in Table 4. Analysis of the soils can be stated as follows:

As it was expected, sandy soil mixed with 10% clay has sand-like behavior (due to having a lot of sand). Hand slamming decreases sand soil density in relation to Proctor test density (compaction of mini cone soil sample was 87% optimum compaction in the laboratory). This incident caused that in the next step by adding 4% of crude oil, the resistance of mini cone tip (around 7%) and, side (around 13%) will increase. It seems that crude oil not only replaces the air in the soil, but as a lubricant, it causes the grains (which did not reach the maximum density due to hand pounding in the previous stage) to slip and, close together. However, the tip and, side mini cone decrease 56% and, 48% by adding oil until 8%, respectively. Therefore, the separation and, reduction of friction occur in the soil grains, due to the increase of crude oil up to 8%. In the case of mixing 4% crude oil with 5% optimum moisture content, tip and, side resistance decrease 30% and, 25% in relation to uncontaminated soil, respectively. Because of hand slamming and, apparent cohesion, strength is enhanced relative to 4% oil condition with its optimum moisture content (4% tip and, 8% side) by adding 4% water to this mixture. The water lubricant effect is less than crude oil so this enhancement of course is less than the previous condition. At last, soil behavior proceeds to the failure point by adding 8% oil with 1% of its optimum moisture content. As three previous analyses have illustrated, due to the soil (sandy soil mixed with 10% clay, with moisture and, with and, without contamination) not reaching its maximum density, by adding 4% crude to the soil, not only it not reduce the resistance, but also it may increase strength in some cases. However, the reduction of resistance is quite tangible with the increase of crude oil to 8%. The calculation of I_c value also shows that the behavior of sandy soil with 10% clay has changed phase from "sand mixtures" to "silt mixtures" with the increase of crude oil and, excess moisture (the first part of Table 4). Of course, it is noted again that due to the lack of 100% compaction in this step, there is no change in the behavior of the two soils (codes 10-9-4-0 and, 10-5-4-0).

With the addition of 20% clay, it was possible to achieve a higher density in the sandy soil mix. However, the soil density did not reach 100% of the Proctor test density, achieving only 95% of optimum compaction in the laboratory. It is also noteworthy that the presence of crude oil introduced apparent cohesion in the sand, producing results similar to those of a sand mixture with 10% clay. This variation was solely due to the reduction of sand and, the increase in clay content in the mixed soil. At this stage, calculating the X value indicates a gradual shift in soil behavior from "sand mixtures" to "silt mixtures," as detailed in the second part of Table 4.

Soil behavior shifted to clay-like more, with increasing clay to 30%, 40%, and 50%. Increasing clay in soils results in closer density to proctor test density due to slamming compaction. Therefore, there are 27%, 30% and, 32% collapse in tip strength, 24%, 23% and, 28% collapse in side strength for sandy soil mixture 30%, 40% and, 50% clay, respectively with 4% rise of crude oil. In addition, there are 48%, 58% and, 44% collapse in tip strength, 44%, 44% and, 46% collapse in side strength, respectively with 8% rise of crude oil. These results are due to the high crude oil impact on the clay contained in the mixture, which eliminated the electrical bond between clay and, water and, consequently soil cohesion. Also, there are reductions 14%, 15% and, 24% of the tip resistance and, 12%, 13% and, 17% of the side compared to non-contaminated conditions, respectively for soils mixture with 4% crude oil and, related optimum moisture content (for sandy soil mixed with 30%, 40% and, 50% clay, respectively 9%, 9.5% and, 13% optimum moisture content). Adding 4% excess moisture to the mentioned soils decreased the tip resistance up to 33%, 41% and, 24% and, the side strength up to 31%, 32% and, 35%, respectively. Due to the presence of more clay in soils, with an increase of crude oil, the cohesion reduced and, the soil resistance decreased significantly. With the increase of crude oil to 8% and, mixing with related optimum moisture content (for 30%, 40% and, 50% clay, respectively 4%, 5% and, 8% optimum moisture content), decreased 42%, 48% and, 39% of the tip resistance and, 35%, 42% and, 42% of the side resistance, respectively, as compared to non-contaminated conditions. This shows the high impact of crude oil on clay. The value of I_c for two types of sandy soil mixed with 30% and, 40% clay, with the increase of crude oil and, excess moisture, changes from the "silt mixtures" to "clays". While the behavior of sandy soil mixed with 50% clay remains in a "clay" state in any condition.

From another perspective, the addition of 4% crude oil to sand mixed with 10% clay resulted in increased tip and, side resistance, likely due to apparent cohesion and, the inability to achieve 100% soil density. However, in sandy soils with 20% clay, this increase was nearly depleted, and, in other soil types, both resistances decreased. This indicates a more significant negative impact of crude oil on soils with higher clay content, as crude oil disrupts the electrical bonds between clay and, water particles over time. Furthermore, adding 8% crude oil to all soils at their optimum moisture content reduced both tip and, side strength. Even high-grade sandy soils containing only 10% and, 20% clay experienced substantial reductions with an 8% increase in oil content. These trends are illustrated in Figure 9. The changes in tip and, side resistance for the 30 soil types tested are detailed in Table 4.

On the other hand, the Ic calculation indicated that soil behavior shifted towards finer soils with increasing crude oil content and, varying moisture levels based on the crude oil content, except in cases where maximum density was not achieved. Specifically, sandy soils mixed with 10% and, 20% clay transitioned from the "Sand mixtures" zone to the "Silt mixtures" zone. Sandy soils mixed with 30% and, 40% clay moved from the "Silt mixtures" zone to the "Clays" zone. Finally, sandy soil mixed with 50% clay remained in the "Clays" zone. These findings are detailed at the bottom of Figure 10.

6- Conclusions

In the environmental contamination context of the soil, crude oil has been considered due to its abundance in oil-rich countries. Uncontrolled extraction causes its overflow and, penetration into the soil layers which will definitely affect the soil parameters of the area. On the other hand, the study of the effects of crude oil on the behavioral parameters of contaminated soil is difficult and, requires high accuracy due to its diffusion in different layers of soil. Quick determination of soil behavior in many cases will be decisive, too.

In this research, the behavior changes of fine-grained soils (including fine sand and, kaolinite clay) were evaluated based on changes in crude oil and, moisture content. At first, the optimum moisture content of five main soil groups (the 2 fine sand mixture with 10%, 20%, 30%, 40% and, 50% Kaolinite clay) without and, with 4% and, 8% crude oil was determined in different situations by the standard Proctor test. Therefore, six modes were considered for each main group, according to the standard Proctor test data. The total number of experiments was performed 30 times. Tests have been performed in the simple chamber (one of the most commonly used equipment in physical modeling). The superiority of this device compared to other physical modeling devices is the large diameter of the upper spout. The mini-cone used for testing is 3.57 cm in diameter, 13.38 cm in friction sheath height, and, 118 cm in total height.

In all the mini-cone tests (Number of thirty tests), the tip and, side resistance of the mini-cone reduced with increasing in the amount of crude oil and, extra moisture. This problem showed that the presence of crude oil reduced resistance in the soils. Of course, it should be noted that the tip and, side resistances increased when the soil was mixed with 4% crude oil in the two types of soils with 10% and, 20% clay. This problem was due to the hand slamming of the soils and, the failure to achieve the maximum density obtained from the standard proctor test in the chamber. Failure to achieve the maximum density caused the creation of air holes in the soils. These holes were filled with crude oil and, increased resistance after mixing with 4% crude oil.

On the other hand, crude oil had a greater effect on the tip resistance in the sandy soils mixed with 10% to 40% compared to their side resistance. While it happened contrariwise in a mixture with 50% clay and, the effect of crude oil is more on the side resistance. This was due to the greater impact of crude oil on soil cohesion with higher clay content.

Finally, the calculation of the Ic value revealed that soil behavior shifted towards that of finer soils with increasing crude oil and, additional moisture content, except in special cases where maximum density was not achieved. For instance, sandy soil mixed with 10% clay (without contamination) transitions from “sand mixtures” to “silt mixtures” as crude oil content increases and, moisture levels change.

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