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Settlement-Time Aspect for Equal-Area Footings with Polygon Shapes Lying on Gypseous Soil

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Keywords:
Polygon footing; Gypseous soil; Collapse settlement; Static settlement.

Highlights:

- *Settlement behavior of polygon shapes footing on gypseous soil.*
- *The settlement experienced by foundation on soil is highly affected by the shape of footing.*
- *Non-regular shape foundation settlement constructed on gypseous soil.*

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Abstract: Gypseous soil is one type of collapsible soil. It is well known in Iraq for causing structural distress to many engineering facilities. It is characterized as having high strength properties as being dry, but when wetted with water, it experiences rapid collapse settlement. The present laboratory study evaluates the collapse settlement for several polygons and non-common footing shapes and compares them. In some structural facilities, such problems may arise when using polygon footing shapes due to reasons regarding non-uniform spacing left for footing, restrictions due to property lines or sanitary works. For this purpose, a large laboratory tank model had lateral dimensions of 0.8× 1.0m and a depth of 0.8m. The studied gypseous soil, with 63% gypsum content, was from Tikrit City, about 200km north of Baghdad/ Iraq. It is compacted to a dry unit weight of 14.82kN/m^3 in the model. The used shapes of footings were a square, circular, equilateral triangle, rectangular, plane strain, trapezoidal, and isosceles triangle. All footings were (100 cm^2) and bear the same applied pressure (40kN/m^2). Both dry and then soaking stages for soil were conducted. The experiments were conducted, such as one test for each tank. The test results revealed that the maximum collapse settlement recorded was in the case of the isosceles triangle, i.e., (settlement/equivalent width) ratio $\Delta s/B$ is 0.24. The least collapse settlement was for the case of square footing with a $\Delta s/B$ of 0.15. The settlement measured when the soil dried was about 1-1.3 mm for all footing shapes, i.e., $\Delta s/B$=0.01-0.013. The collapse settlement stopped after 5-7 days, while the dry condition settlement took less than one hour to level off and end.

الجانب الزمني للهبوط لأُسس متساوية المساحة مع أشكال مضلعة مستندة على تربة جبسية

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الخلاصة

التربة الجبسية هي أحد الانواع من مجموعة التربة القابلة للانهيار. وهي معروفة في العراق بأنها تسبب مشاكل للعديد من المنشآت الهندسية. تتميز التربة بخصائص قوية عالية عندما تكون جافة، ولكن عند ترطيبها بالماء، فإنها تتعرض للهبوط السريع (الانهيار). تختص هذه الدراسة المعملية بتقييم هبوط الانهيار للعديد من أشكال الاسس المضلعة وتقديم تحليل مقارنة بينها. في بعض المرافق الهيكلية قد تنشأ مثل هذه المشكلة بسبب استخدام أشكال غير منتظمة للاسس لأسباب تتعلق بالمسافات غير المنتظمة التي تُترك للاسس، والقيود بسبب حدود الملكية أو الأعمال الصحية، وما شابه ذلك. لهذا الغرض، تم استخدام نموذج خزان مختبري كبير بأبعاد جانبية ٠,٨ x ١,٠ م وعمق ٠,٨ م. التربة الجبسية المستخدمة في البحث التي تحتوي على ٦٣٪ من محتوى الجبس، تم جلبها من مدينة تكريت التي تبعد حوالي ٢٠٠ كيلومتر شمالاً إلى العاصمة بغداد / العراق. تم تحضيرها على وحدة جافة بوزن ١٤,٨٢ كيلو نيوتن / متر مكعب في النموذج. أشكال الاسس المستخدمة هي مربع، دائري، مثلث متساوي الأضلاع، مستطيل، شريطي، شبه منحرف، ومثلث متساوي الساقين. جميع الاسس متساوية المساحة (١٠٠ سم ^{٢}) وتتحمل نفس الضغط االمسلط (٤٠ كيلو نيوتن / م ^{٢}). يتم تنفيذ كل من المراحل الجافة ثم تُغمر التربة بالماء. يتم إجراء التجارب بمعدل اختبار واحد لكل خزان. بينت نتائج الاختبار أن الحد الأقصى لهبوط الانهيار المسجلة في حالة اساس المثلث متساوي الساقين، أي أن نسبة (الهبوط / العرض المكافئ) $\Delta s / B$ هي ٠,٢٤. وأقل هبوط للانهيار كانت في حالة اساس مربع مع $\Delta s / B$ تساوي ٠,١٥. تم قياس الهبوط عندما تكون التربة جافة فتتراوح (١-١,٣) ملم لجميع أشكال الاسس، أي $\Delta s / B$ تساوي (0.01-0.013). توقف هبوط الانهيار بعد ٥-٧ أيام بينما استغرق هبوط الحالة الجافة أقل من ساعة واحدة.

الكلمات الدالة: الاساس المضلع، تربة جبسية، الهبوط المفاجئ، الهبوط الستاتيكي.

1.INTRODUCTION

Collapsible soils are spread worldwide, it is estimated that 1.5% of dry earth crust is covered by collapsible soils [1]. They mostly exist in Australia, Argentina, Spain, large parts of Asia, and Europe. They cover 30% of the Iraqi area, exist in the western desert, and extend to some northern parts of Iraq [2]. These soils experience large settlements as they are wetted with water [3]. The dry gypseous soils experience high strength [4]. These collapsible soils are of several types, namely, calcareous, gypseous, salty, and Sabkha. The amount of gypsum in the soil to become gypsiferous and trigger constructional problems is a concern among researchers. For instance, Alphen and Romero [5] – 2% called gypsiferous. Saeed and Khorshid [6] – 6% called gypsiferous. Others, such as [7], presented classification tables, Table 1.

Table 1 Classification of Gypseous Soils [8].

%Content of gypsum in soil	Soil classification
0-10	Slightly gypsiferous
10-25	Moderate gypsiferous
25-50	Highly gypsiferous
>50	Gypcrete

In this study, gypseous soil is considered. In real engineering life, not all footings are of common and regular shapes. Most of these footings are rectangular, circular, or square. Sometimes, the property lines in real estate impose, in reality, very peculiar foundation shapes. The authors had faced many such problems in their long engineering life span. A study by [9], studied laboratory models using normal soils, stated that narrow footings shape showed higher settlement than wide footings of the same area. Patel and Bhoi [10], in their 3D FE study using Plaxis software, showed that the presence of an adjacent foundation reduced bearing capacity for round shape and increased rectangular shape footing. Kozman et al. [11] found that bearing capacity increased in the circular, square, and rectangle for a relative density of 80%. They partially attributed that to the confining effects. Hazzard and Yacoub [12] conducted a Finite element (FE) numerical modeling analysis for triangular footing with a test program to predict an equivalent rectangular analysis derived from the reduced area of loaded footing for bearing capacity. On the other hand, Abid Awn and Abbas [13] presented an FE comparison study with analytical results for irregular and uncommonly shaped footings with error minimization. Several studies, such as [14- 16], studied different techniques for improving collapsible soil properties. Obead et al. [17] investigated the time required for unsaturated collapsible soil to reach collapse. In [17], the Artificial Neural Network predicted the permeability of Gypseous Soil. A study by Ahmed and Zedan [18] showed that adding ceramic waste to gypseous soil improved bearing capacity and reduced settlement to a limited extent. Zedan and Abbas [19] showed that replacing the gypseous layer with the sand layer improved the bearing capacity when the gypseous soil was compacted to field density and soaked with a relative density of sand (80%). The present research studies how different shapes of footings bearing with the same area can affect the collapse potential of structures carried by such footings. Sometimes, the engineering state of buildings dictates the used footing shapes. On the other hand, there are some cases in many engineering facilities where the foundation designer can choose the footing shape. As such, this paper provides a good guideline for choosing the footing shape to reduce the settlement for the collapse potential.

2.EXPERIMENTAL WORK

The totality of work is conducted in the laboratory, and no field model was performed, although the full-scale model will provide better close-to-reality data.

2.1.Soil Used

The gypseous soil used in this study was from Tikrit City/Saladin governorate, about 200 km north of Baghdad, as shown in Fig. 1. The gypsum content of such soil was 63% (using the EDTA method (an acronym for ethylenediamine tetra-acetic acid), which is rather high ratio. The grain size distribution (ASTM D6913) is shown in Fig. 2. Two methods were used to determine collapse potential: single and double oedometer tests. In this study, the single oedometer test was conducted. Regardless of being gypseous soil, it was regarded as sandy soil. According to Bowles [20], the soil is trouble.

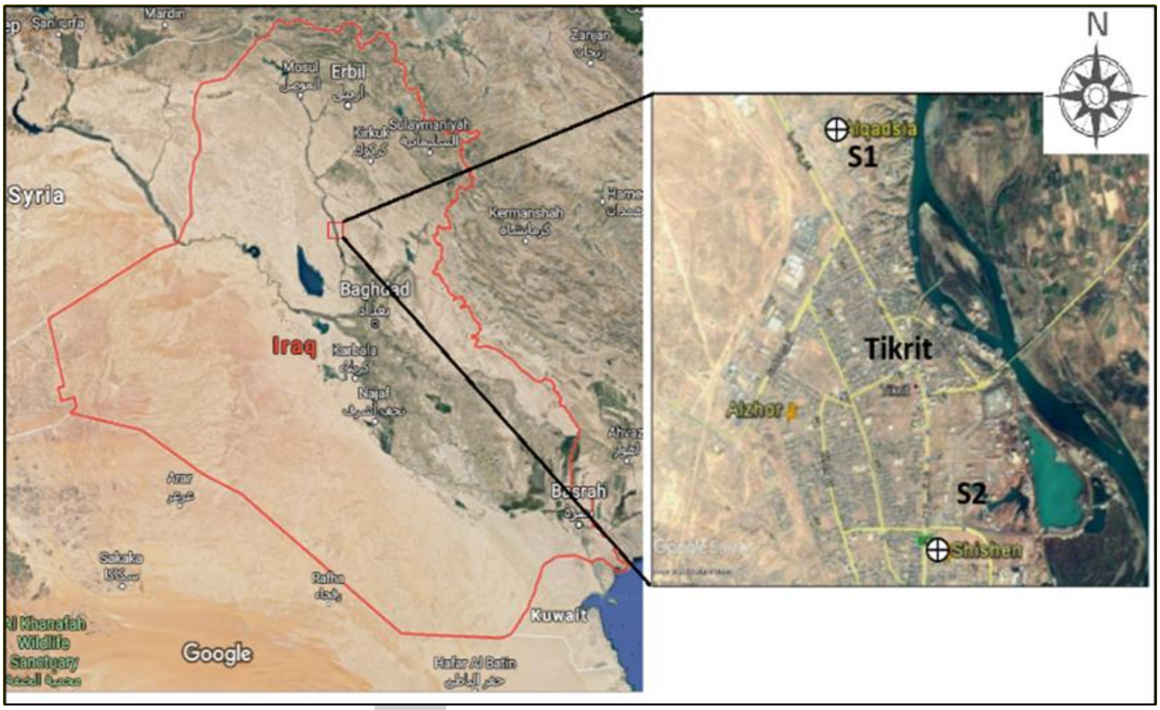

Fig. 1 The Gypseous Soil Location.

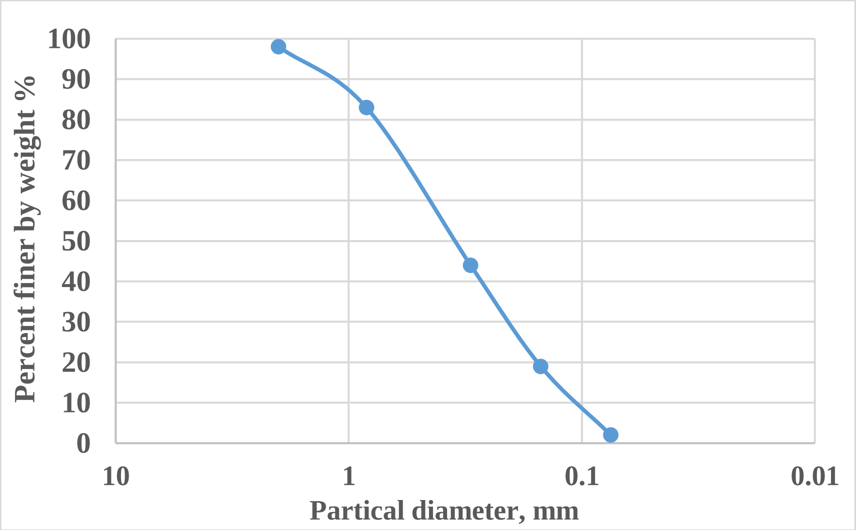

Fig. 2 Grain Size Distribution for the Soil.

Four separate direct shear box tests (ASTM D3080) were run on a dry and wet basis (consolidated drained test) to measure the gypseous soil friction angle. A standardized calibrated shear box test machine was used in these tests. The (average) friction angles were 31^{o} and 30^{o} for dry and wet, respectively. According to [21, 22], the friction angle of gypseous soil was slightly decreased using the shear box as the soil was tested in dry and soaked states. It is intended to use a fixed (well-controlled) dry unit weight in all experiments as 14.82 kN/m^3. It is worth mentioning that several trials were conducted to determine the appropriate energy to reach the desired density. The density represented the in-situ one, conducted at the site where the soil sample was collected. The physical properties of the soil are shown in Table 2.

2.2.Laboratory Testing Setup

Figure 3 shows a schematic view of the testing setup manufactured by the authors using materials from the local market. It consisted of the following parts:

Footings: The footing used in the study bears the same contact area to provide a pressure of 40kN/m². It represents the stress from two- to three-story domestic buildings, as the same loading was used for the tests. This pressure generally represents the normal rate imposed for domestic houses in Iraq. The thickness of all footings was 15mm of stainless steel. The dimensions of the studied footings are listed in Table 3. In the experiments, the following were used:

1- A steel container tank had dimensions of 800×1000mm and a depth of 800mm. The tank had three openings with valves for pushing water inside the tank and a transparent pipe to monitor the water level in the tank.

2- A heavy steel table, for the container to rest on to ease control of soil placement and later the experiments.

3- Steel loading frame to rest on the footing below and mount the bearing loads.

4- A steel holder to carry two electronic dial gages (a 0.01mm sensitivity). It had a flexible arm to zero the dial readings.

5- Water supply system to saturate the soil.

Table 2 Physical Properties of Gypseous Soil Used for Testing.

Property		Value	Specification
Grain size analysis	D10 (mm)	0.11	
	D30 (mm)	0.25	
	D60 (mm)	0.70	
	Coefficient of uniformity, Cu	6.40	ASTM D6913
	Coefficient of curvature, Cc	0.81	
	Passing sieve No. 200 (%)	2	
	Classification of soil based on (USCS)	SM	
	Specific gravity, Gs	2.39	ASTM D 854
Atterberg's limits	Liquid limit (L.L)%	20	ASTM D4318
	Plastic limit (P.L)%	N.P	
	Plasticity index (P.I)	---	
Direct Shear Test	Angle of Internal Friction (Ø) in dry	31	ASTM D3080/ D3080 M-11
	Angle of Internal Friction (Ø) in soaked	30	
Compaction Characteristics	Max. Dry unit weight (kN/m³)	16.35	ASTM D-4253
	Min. Dry unit weight (kN/m³)	11.92	ASTM D-4254
	Test unit weight (kN/m³), γd test	14.82	
	Collapse Potential	7.8	ASTM D5333

Table 3 Shapes and Dimensions of Irregular Footings Used.

Type of footing	Dimensions
Square footing	Width = 100 mm
Circular footing	Diameter = 113 mm
Equilateral triangle	Length of side = 152 mm
Rectangular footing	Length/width = 2, (L= 141 mm, B= 71 mm)
Strip footing	L = 200, B = 50 mm (≈ plane strain condition)
Trapezoidal footing	height = 100mm, small side/big side = 50/150 mm
Isosceles triangle	Base=80mm and height =25mm

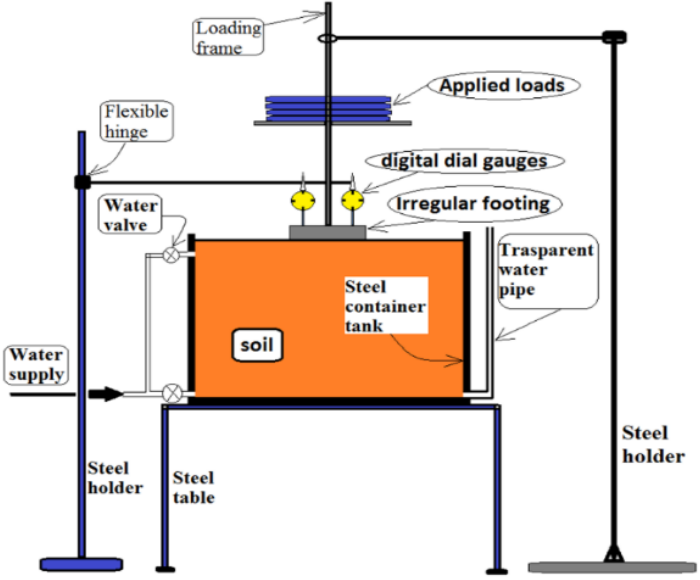

Fig. 3 Setup for Laboratory Model, 0.8x 0.8m Steel Tank and One-Meter Length.

2.3.Preparation of Soil

First, soil from the site was mixed thoroughly to get a homogenous collapsible soil. The soil was then divided (separated) into batches of about 20-25 kg; each batch was placed into a double nylon bag, stored well, and preserved in the laboratory room, ready to be used when needed. As such, each nylon (double) bag should contain a homogeneous soil representing the native in-situ soil or nearly so. To prepare the soil in the tank, one bag for each time after another was brought, and the soil was mixed again and placed in the container (or the tank) in air room-dried condition, or more precisely, in air room- dried condition. To reach a dry unit weight of 14.82 kN/m^3, several trials were conducted. It is worth mentioning that the soil was compacted into layers of 100 mm each, using an electrical compactor shown in Fig. 4. The work was carefully done to provide a unified dry density as possible as one might get. The container depth was 800 mm, leaving seven well-compacted layers; the last 100mm were left soil-free. As the seventh layer (the last layer) was completed, the soil surface was leveled off carefully and covered with a nylon sheet. The container was left with the compacted soil for the next day. In other words, the container was left for 24 hours before getting tested. After finishing the test, one week later, the soil in the container was dumped out and never used again. In other words, new soil was used for every test. A large quantity of soil was consumed in this research.

Fig. 4 Electrical Compacter Used.

2.4.Testing Procedure

After the soil was well prepared and compacted into the container, it was left for one day, as mentioned before. The footing was carefully placed on the surface of the soil. Two dial gauges were placed on the top of the footing. These dial gauges were held in position by a stand steel holder separated by a safe distance entirely from the container and the loading frame. Each irregular footing was in-grooved in its centroid. As a result, when the loading frame shaft was placed in this groove (hole), the loading was applied, and the footing would transfer equal bearing pressure on the soil surface. This procedure is very important to eliminate any rotation of footing during testing. To monitor footing rotation, the two dial gauges were used for that purpose. When the two dial readings during testing differed, i.e. footing rotation took place, and the whole experiment was stopped and eventually repeated. When the two dial readings were rather close enough, i.e., no footing rotation occurred during the test. The average dial readings were used for plotting the settlement–time curves. The groove (hole) in the footing was greased to reduce friction between the loading frame shaft and the footing, leaving the last to rotate freely. After placing the footing on the soil and installing the two dial gauges, the loading frame was placed on the footing. Dial gauges were set to zero, and the loading was gradually and carefully applied on the loading frame until reaching a pressure of 40kN/m^2, representing the start of the test and settlement was recorded with time. The experiment was stopped (for dry basis) when the dial readings reached a constant value, i.e., no more settlement occurred. Until this stage, the soil was dry or, more precisely, air-dried. This stage lasted about one hour at most, representing the end of the first stage. The second testing stage started after one hour by opening the inlet water valve to initiate the soaking soil. Penetrating water through soil, i.e., the water level in the container, was monitored through a transparent pipe. When the soil was fully saturated, the water valve was closed, and the settlement reading continued for one week until negligible dial readings were recorded. The soil took several hours to saturate fully. Low water pressure was applied to saturate the soil to avoid any boiling in the soil. When the test was finished, another test was run with different footing and new soil. The progress of water flow was carefully monitored through transparent pipes. Since the soil used was sand, saturation was shortly reached, which was also checked out by examining soil specimens. The saturation process was vital and due care was played to ensure a fully saturated soil; otherwise, incorrect test results would be reached.

3.RESULTS AND DISCUSSION

It is well known that the original bearing capacity equation was initially derived successfully by Terzaghi [23] in the early of the last century. His model has remained till now as the basis of the bearing capacity of the soil. He assumed the famous aspect of the passive and active stress triangles generated under and to the sides of a strip footing. Initially, as loading to footing begins, the soil will behave elastically, i.e., a linear relation between stress and settlement, which will go on for short until a local shear failure shows up under the footing and in a small soil zone directly under the footing; here, this soil zone will change from an elastic to a plastic state. The footing can still experience a much larger load beyond that until all triangles of active and passive zones turn up into plastic (continued strain without further stress), i.e., the ultimate capacity of the soil. As the authors believe, this scenario is applicable and valid for all footings with non-common shapes. However, the shape and size of the active and passive zones will surely diverge from the standard–theoretical strip footing. How much this irregular footing shape will diverge? This is a question that needs to be answered by laboratory models. The larger the size of plastic zone propagation, the larger the bearing capacity is reflected in this paper by the time-settlement curves of laboratory models. The following results of such curves in research confirm the scenario since all footings have the same area. Otherwise, all settlement-time curves will be similar and may differ very little, which was not the case recorded and measured here. Thus, the footing shape affected the soil carrying capacity. As such, this paper looks for the differences in carrying capacities for different irregular footing shapes. Figure 5 shows the end of the test for the square footing. The settlement of the footing was obvious, the settlement-time curves are presented in Figs. (6-12), while Fig. 13 shows the whole curves gathered. A fast look at the curves shows that the general behavior trend is the same for all. They are characterized by very small settlement for the dry stage, which lasted one hour, followed by drastic suppression in the soaking stage, which continued for about 40–50 hours. After that time, and for all footings, the settlement reading was almost leveled off, signing the end of the collapse settlement. As expected, the dry gypseous soil had high strength properties, and as such, the immediate settlement (not collapse) was rather low, i.e., about 1-1.3 mm.

Fig. 5 End of the Square Footing Test**.**

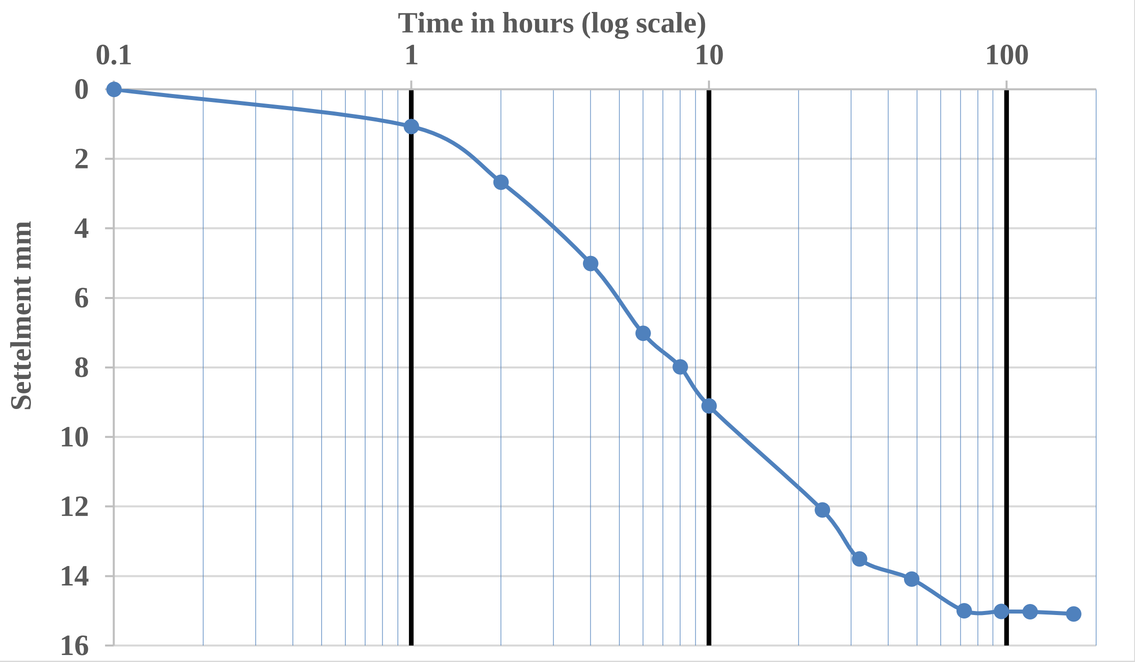

Fig. 6 Settlement-Time Curve for the Square Footing.

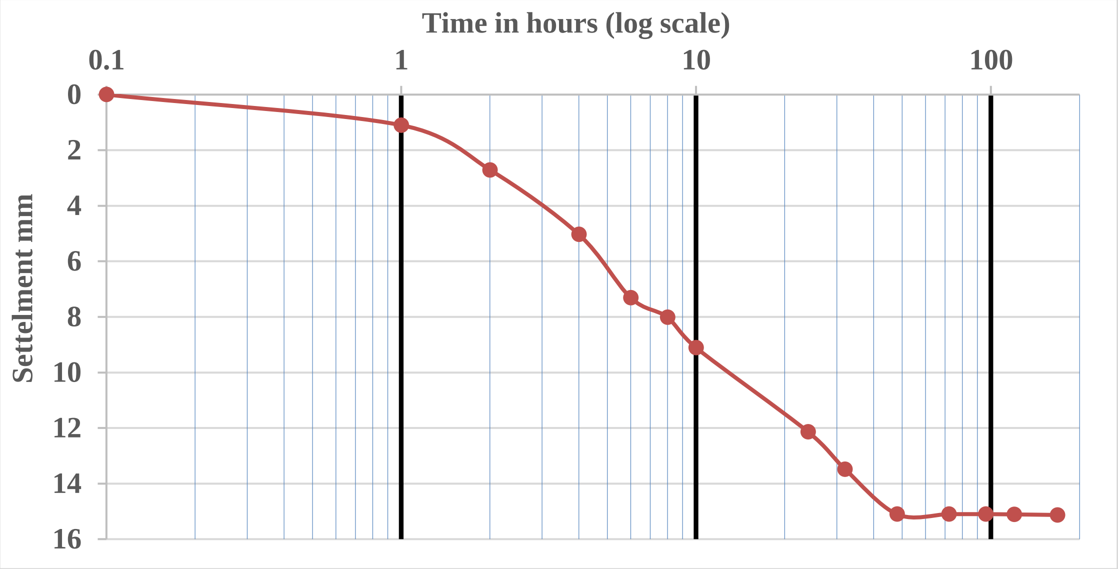

Fig. 7 Settlement-Time Curve for the Circular Footing.

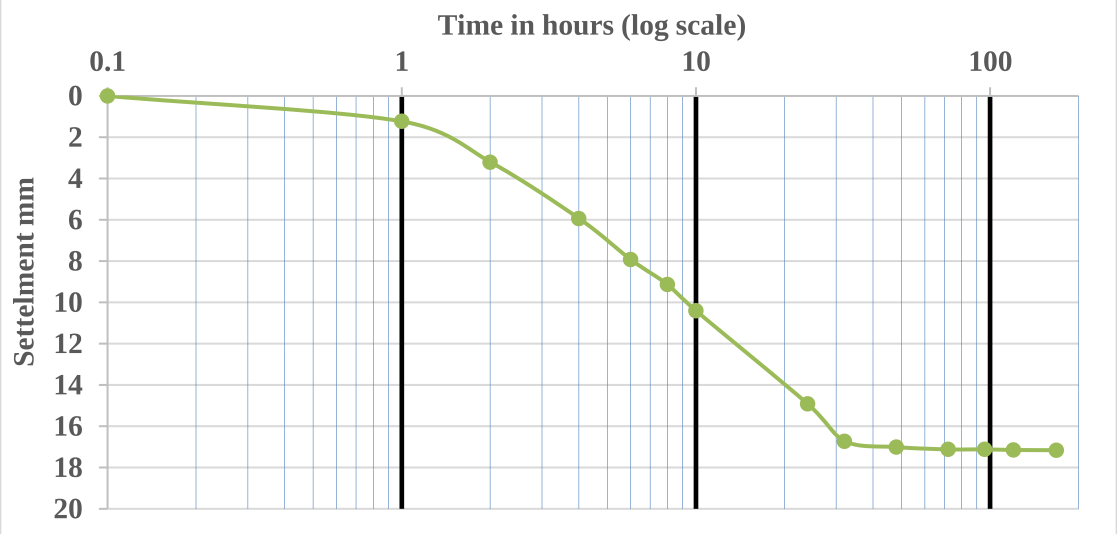

Fig. 8 Settlement-Time Curve for the Equilateral Triangle Footing.

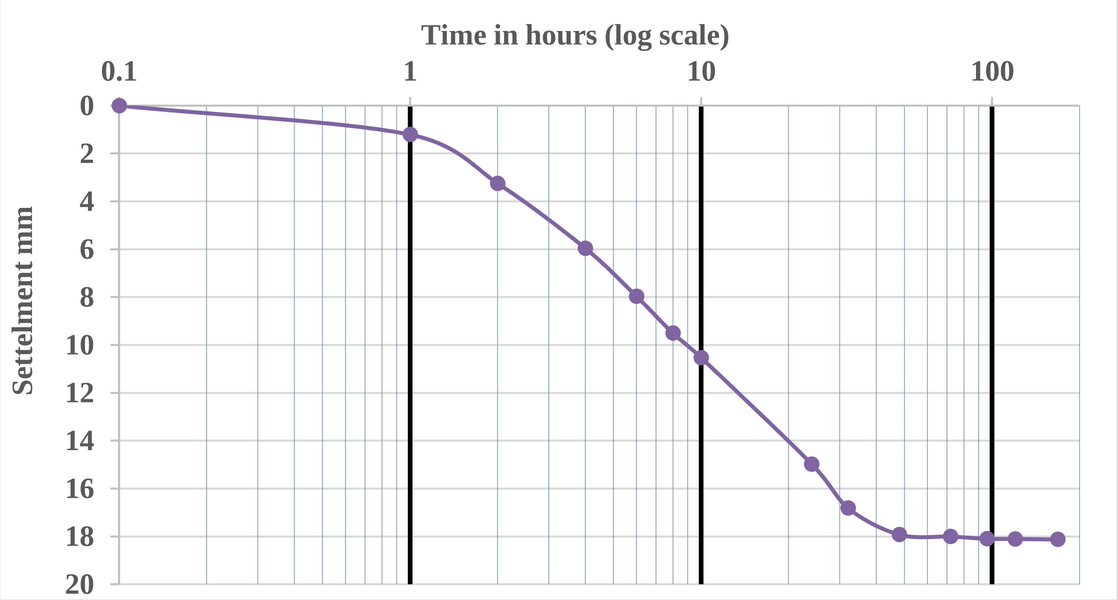

Fig. 9 Settlement-Time Curve for the Rectangular Footing.

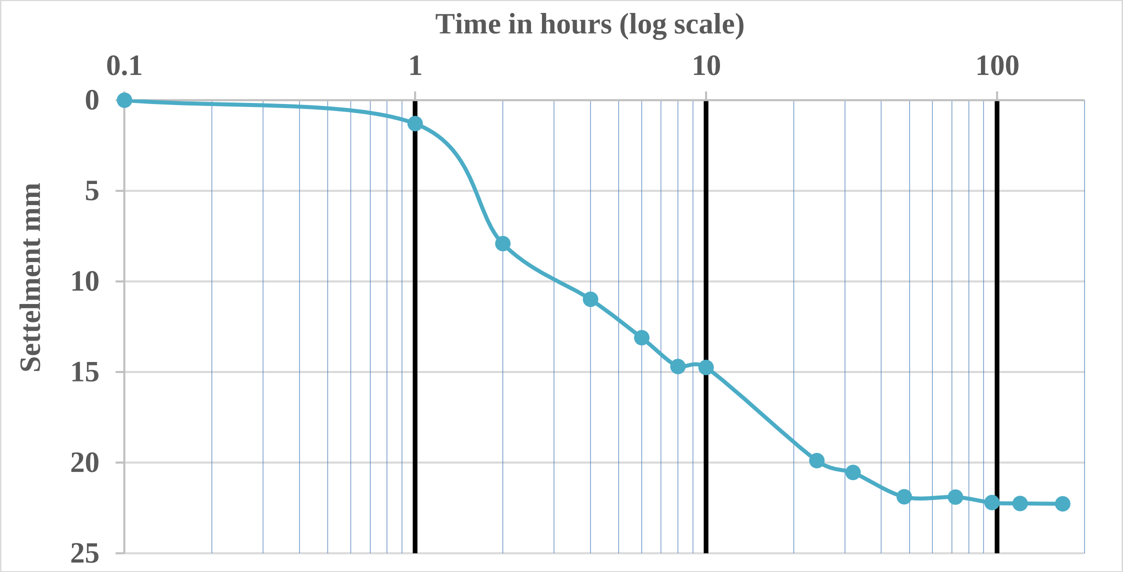

Fig. 10 Settlement-Time Curve for Plane Strain Footing.

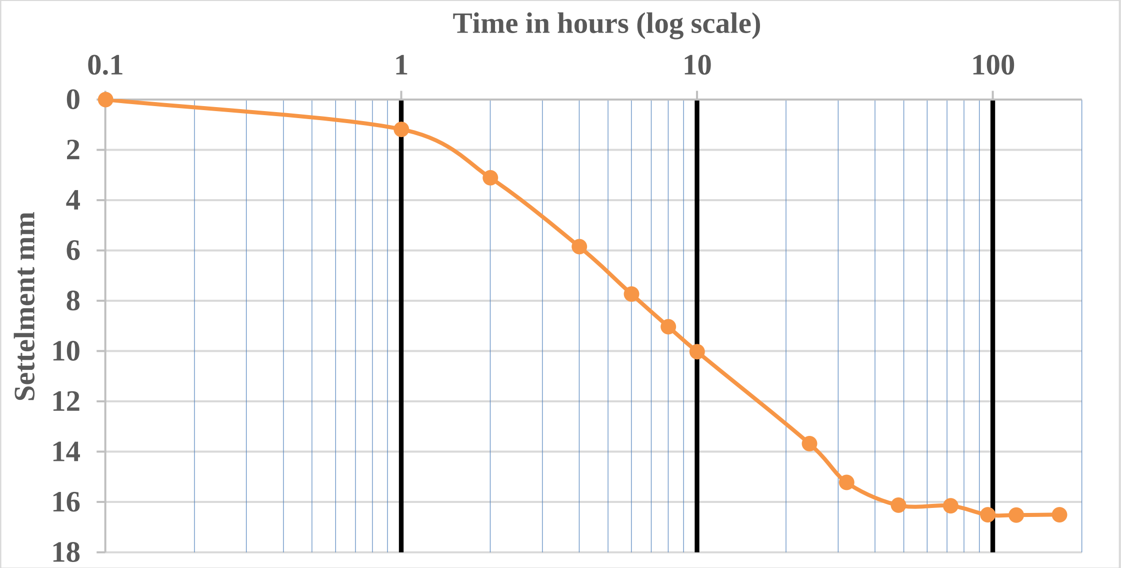

Fig. 11 Settlement-Time Curve for the Trapezoidal Footing.

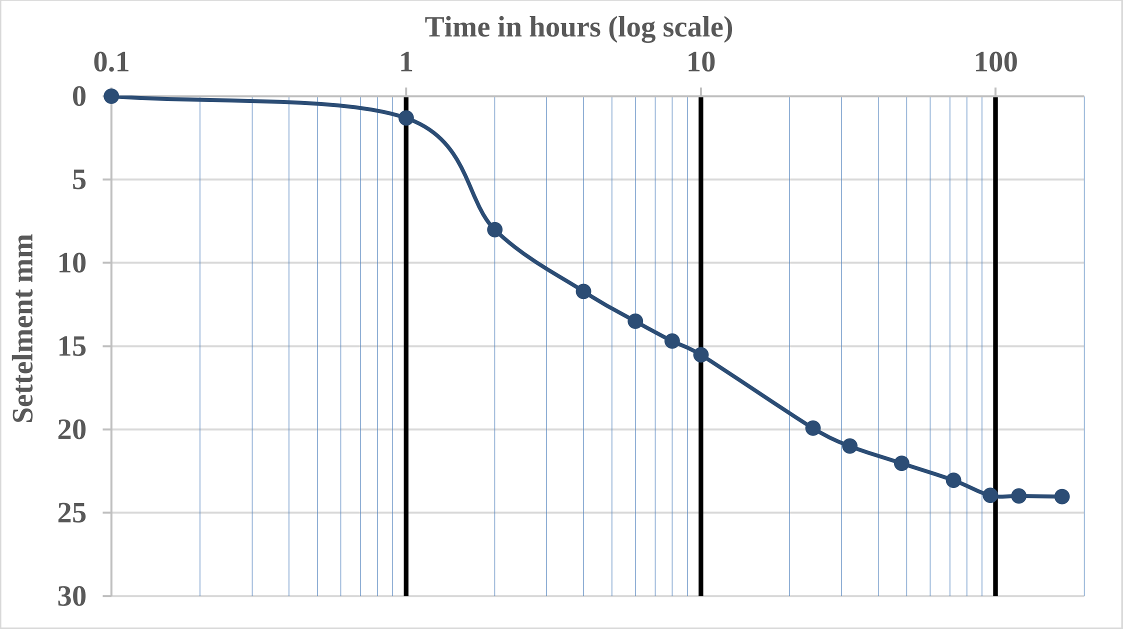

Fig. 12 Settlement-Time Curve for the Isosceles Triangle Footing.

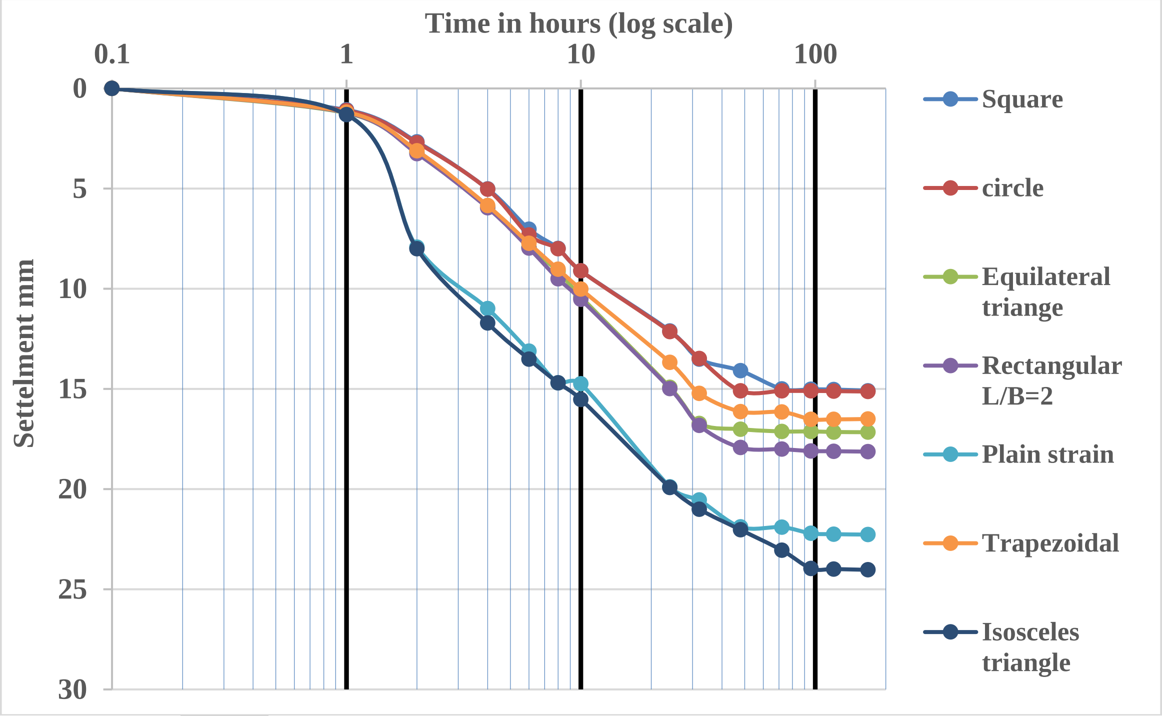

Fig. 13 Settlement-Time Curve for Whole Irregular Footing Shapes.

As stated by many researchers and handbooks, such as [20], in the case of using circular footing and for ease of calculations, it can be converted to an equivalent square footing. However, no regulations are recommended regarding other shapes. Since all footings have the same area, thus if all footings in this study are converted to a square footing, they will bear the same equivalent width (B), i.e., 100 mm. In this case, the footing should experience the same collapse settlement if the shape of the footing has no effect on the soil collapsibility. However, the footing shape does indeed have some conflict in settlement. So, the equivalent square width is 100mm, as in the case of square footing. The authors chose this width to ease interpreting settlement readings as the famous ratio quantity (settlement/width=Δs/B) is directly recognized by dividing the settlement number by 100. For instance, the maximum ratio of Δs/B recorded was 0.24, the isosceles triangle case. Test results revealed that the collapse settlement recorded in ascending order were as follows:

1- Square footing, Δs/B= 0.1509
2- Circular footing, Δs/B= 0.1513
3- Trapezoidal footing, Δs/B= 0.165
4- Equilateral triangle, Δs/B= 0.1716
5- Rectangular footing, Length/width = 2, Δs/B= 0.1813
6- Strip footing; L = 200, B = 50 mm (plane strain condition), Δs/B= 0.2227
7- Isosceles triangle, Δs/B= 0.2403

These results indicate that if the footing shape was "an encircled shape," i.e., having equal width with length, the collapse settlement seemed smaller than the footings having an extreme width/length ratio, as seen in the case of an isosceles triangle. As such, a soil engineer should resize, if possible, his design by this result when dealing with collapsible soil. When the footing shape has edges extending out of the area, the settlement is expected to rise. This conclusion needs some theoretical background. Unfortunately, the collapse settlement has mostly relied on empirical formulas with some laboratory experiments to determine its degree of severity, such as the double oedometer or the knight test. As a comparison study, the results from Fig. 13 show that the square and circular footings behavior is almost identical; they differ only in small numerical values. Both resulted in the smallest amount of depression, i.e., Δs/B=0.151. Although this number was the smallest among the other types of footings, it is a relatively high ratio in real engineering life. In other words, in the case of two meters' width of footing, for instance, a settlement of about one foot is expected. This number is very high for any footing to withstand unless special measurements are to be taken, starting with the soil. Interpreting the results is mostly difficult since it cannot be relied on theoretical aspects only. The failure criteria for soil bearing capacity were well experienced initially by Terzaghi [23] in the middle of the last century for ordinary soils, and all following scientists used the same concept he presented with modifications. No theory has floated to the surface ever since then. The situation of the problematic soils is an exception, and the collapsible soil is critical the most among them. No failure criterion is well standardized and approved for collapsible soils. The case explains why it resorted to laboratory models extrapolated to full-size footing associated with the field experience. The propagation of the stress bulb in the soil is based on the width of the smaller size footing. However, this is true for regular-shaped footings, such as rectangular. The case of this study is irrelevant to that. So, to adhere to a limit for settlement based on the real width of footing is not sound, and since the shape is irregular, the relay on equivalent footing width is most (not totally) logical. The studied gypseous soil has two different behaviors: initially, when it was dry and once again when it was assessed to water, causing the soil to collapse. These two behaviors will indeed escalate the problem more. The trapezoidal, then the equilateral triangle, and the rectangular footings were close to each other; they bore Δs/B ratios of 0.165, 0.172, and 0.18, respectively. These footings experienced much higher collapse settlement than the square and circle. The last two footings, isosceles triangle and strip footing (plane strain footing), showed almost identical behavior, although the isosceles experienced a slightly higher settlement. However, from zero time to 20-30 hours, the settlement curves were almost identical. Only after 30 hours; the isosceles triangle showed higher depression than the strip footing. The Δs/B ratio for the isosceles triangle showed the highest value, i.e., 0.24. This collapse settlement value is extremely high for any engineering facility to tolerate, making the collapse settlement of this type of gypseous soil very dangerous to buildings. Strictly speaking and from logic and common sense, it seems more “realistic” to believe that as long as any footing with any shape whatsoever and bearing identical stress should suffer the same settlement as other footing having the same loading but with a different shape. The shape factor in the bearing capacity equation has some adjustments regarding the plane strain of the footing translated to rectangular or square, which opposes the latter consequence. However, the case is unknown for collapsing soils. An impact does exist regarding footing shape in the case of collapsing soil, as in the case of ordinary soil. This cap is believed to be reduced by resorting to experimental models. As an outcome of this study with the collapsible soil, as the footing shape was closest to the regular equidimensional shape, the less settlement was for the same area and stress, and it is safer. A soil engineer should put this fact in his active vocabulary. In real-life engineering situations, many problems may arise regarding using irregular shapes of footings, which may come from restricted areas, non-uniformly shaped, and irregular property lines or cut-off areas due to sanitary installations. The trapezoidal and triangular footing are common. The usual equations for calculating the settlement for footing resting on normal soils (not problematic) cannot be applied on collapsible soils, leaving laboratory models to close the gap with the help of some empirical equations. All shapes of footings have the same area and applied soil surface pressure. Using the conventional “equivalent width” for settlement calculations is no longer valid since all footings have the same equivalent width. However, as laboratory results revealed, quite different settlements were recorded; however, all of them were very high.

4.CONCLUSIONS

In the present study, a laboratory model was built to simulate and measure the collapse settlement of different footings having non-common shapes. All footings had the same area and contact pressure, namely 40kPa. The settlement was recorded while saturating the collapsing soil, and the following outcomings were drawn:

1- All footing shapes experienced very little settlement when the soil was dry (about one millimeter), and the differences between them cannot be concluded, which is attributed to the low bearing stress applied onto the soil. To solve this problem, the tests were repeated with much higher stress.

2- It took less than one hour for the dial gauge readings to level off, and settlement was nearly stopped in the case of dry soil loading conditions, which was obvious since only immediate settlement occurred.

3- For the soaked stage of settlement (the collapse settlement), the general behavior trend for all curves was similar but different in quantities.

4- The final recorded settlements in ascending order were as follows:
   a. Square footing.
   b. Circular footing.
   c. Trapezoidal footing.
   d. Equilateral triangle.
   e. Rectangular footing, Length/width = 2
   f. Strip footing; L = 200, B = 50 mm (plane strain condition).
   g. Isosceles triangle.

The smallest (Δs/B) ratio measured was 0.151 in the square footing case, and the highest (Δs/B) ratio was 0.24 in the isosceles triangle case.

5- As long as the footing shape was “an encircled shape,” equal width with length, the collapse settlement was smaller than footings with an extreme width/length ratio, as seen in the isosceles triangle case. As such, a soil engineer should resize, if possible, the design according to this result when dealing with collapsible soil.

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