

## **Experimental and Theoretical Determination of Settlement of Shallow Footing on Liquefiable Soil**

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### **ABSTRACT**

A high settlement may take place in shallow footing when resting on liquefiable soil if subjected to earthquake loading. In this study, a series of shaking table tests were carried out for shallow footing resting on sand soil. The input motion is three earthquake loadings (0.05g, 0.1g, and 0.2g). The study includes a reviewing of theoretical equations (available in literatures), which estimating settlement of footings due to earthquake loading, calibration, and verification of these equations with data from the shaking table test for improved soil by grouting and unimproved soil. It is worthy to note that the grouting materials considered in this study are the Bentonite and CKD slurries. A modification to the seismic settlement equations, by statistical analysis using SPSS software, had been done to account for the liquefaction state. The modified equation showed a good convergence with the measured settlement values.

**Keywords:** Experimental evaluation, Bentonite, Grouting, Liquefaction, statistical analysis, Settlement, Cement kiln dust.

### **ايجاد النزول الحاصل للاسس الضحلة عمليا و نظريا للترب المعرضة للتسييل**

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### **الخلاصة**

عند حدوث الهزات الارضية تتعرض الترب الرملية الضعيفة المشبعة الى احتمالية حدوث ظاهرة التسييل و هو ما يؤدي الى فشل في المنشآت الموجودة و حدوث نزول كبير في الاسس الخاصة بهذه المنشآت و خاصة الضحلة منها. ولهذا الغرض تم اجراء سلسلة من التجارب المختبرية باستخدام المنضدة الهزازة مع تمثيل للاسس الضحلة المنشأة على ترب رملية مشبعة و ضعيفة القوام, حيث تم استخدام عدة مستويات من التعجيل المسلط (0.05g, 0.1g, 0.2g) لتمثيل و دراسة سلوك التربة اثناء الاهتزازات و تأثيرها على الاسس الموجودة. ولتقليل التسييل الحاصل نتيجة تراكم ضغط ماء المسام تم معالجة التربة لتقليل

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التأثير من الحمل الاهتزازي تم استخدام طيقة الحقن النفاذ بواسطة مواد متوفرة محليا كطين البنتونايت و غبار مرسبات السمنت. من المعروف ان حساب الهبوط للاسس يتم بواسطة معادلات نظرية اعدت لهذا الغرض للحالات التي يكون الحمل فيها داينميكي كالهزات الارضية و غيرها, تعتمد هذه المعادلات على عدة عوامل بعضها له علاقة بالتربة و الاخر بشدة الحمل و تردده. ومن خلال دراسة العوامل المؤثرة لوحظ عدم وجود او ادخال لعامل ازدياد ضغط ماء المسام ودوره في حدوث التسييل والذي يؤدي الى نزول كبير في الاسس. وعليه تم اقتراح تعديل على المعادلات العاملة لغرض استيفائها لجميع العوامل المؤثرة كذلك جعل الصيغ المعدلة تلائم اليات التحسين المقترحة للتربة في هذه الدراسة و امكانية تطبيقها على اليات اخرى او طرق مغايرة. ومن خلال التحليل الاحصائي و مقارنة النتائج بالبيانات المستحصاة من التجارب العملية وجد ان الصيغ المطورة مقارنة و ملائمة لنتائج التجارب و يمكن استخدامها كصيغ معتمدة في حالات مماثلة وفي تقييم و تحديد النزول المتوقع للاسس في مواقع مشابهة. **الكلمات الرئيسية:** تقييم التجارب المختبرية, التسييل, الحقن بالبنتونايت, الحقن بغبار مرسبات السمنت, التحليل الاحصائي.

## 1. INTRODUCTION

Earthquake caused one of the most destructive natural disasters leading to heavy losses of life and property. Unfortunately, the earthquakes are, so far unpredictable and unpreventable. The well understanding of earthquake and/or dynamic loading basics and the expected behavior of the soil under this type of loading will helps to select the adequate measurement, tests, reduce the negative effects and treatment of the specified site. The earthquakes have many hazards on different fields; in soil mechanics and foundation engineering field the earthquake have many destructive and aggressive effects, including shear failure, total and differential settlement. Foundation failure and/or damage of existing buildings may occur during earthquake if liquefaction of the soil is happening are due to the following features:

- 1- Excessive and rapid reduction in bearing capacity of the underlying soil.
- 2- Excessive total, tilting, and/or differential settlement of the existing buildings.
- 3- Boiling and heaving of the underlying layers which cause an additional settlement to the shallow foundation.

The above destructive failures push many researchers to study, investigate, analyze, and predict the soil and foundation behavior during earthquake to avoid or reduce the above destructive effects. The developed studies and researches followed and depended different approaches, theories, and hypothesize so as to simulate the failure mechanism. Some of these approaches are numerical, empirical, and/or experimental, all of them depend on the available parameters related to the nature of the soil, soil condition, and ground motion parameters. They analyze soil characteristics and its field condition as a control agent to its behavior during earthquake, some of them regarded that the ground motion parameters are respect the governing agent, while the others depend on the combination of both agents as a governing agent, which is more reliable.

## 2. PREVIOUS STUDIES ON SEISMIC SETTLEMENT DETERMINATION

(Richards et al ,1993) proposed a simplified approach to estimate the dynamic bearing capacity equation and seismic settlement  $S_{Eq}$  of a strip footing for assumed failure surfaces as in equation (1). There is hardly any experimental verification of these theoretical solutions. Hence, it is a good chance to validate these solutions.

$$S_{Eq} (m) = 0.174 \frac{V^2}{A.g} \left( \frac{k_h}{A} \right)^{-4} . \tan \alpha AE \dots \dots \dots (1)$$

Where:  $S_{Eq}$  is the settlement due to earthquake,  $V$  = peak velocity for the design earthquake (m/sec),  $A$  = acceleration coefficient for the design earthquake,  $g$  = acceleration due to gravity



( $9.81 \text{ m/sec}^2$ ), the values of  $k_h^*$  and  $\tan\alpha_{AE}$  can be obtained from figures and tables as illustrated and cited in **(Das and Rammana 2011)**.

**(Stamatopoulos et.al ,2004)** were conducted series of laboratory tests by using cyclic direct shear apparatus on saturated Greek sand at different densities and OCR. The main measured factor in the executed tests is the volumetric strain constant volume and controlled shear strain. The test condition was regarded similar to earthquake conditions. The assumption depends on the fact that during earthquake the soil tend to become denser which cause and excessive settlement and structural damages.

The evaluation of volumetric strain was executed by using different approaches at different soil states (dry and saturated), the authors mentioned to the accuracy of their findings with other studies depending on the soil condition and loading history.

**(Puri and Parakash , 2007)** reviewed several aspect of pile and shallow footing that subjected to seismic loading at liquefiable and non-liquefiable soils; they analyze and discussed the reduction in bearing capacity and the increment in expected settlement of shallow foundation depending on empirical approach that relate the motion parameters such as acceleration of earthquake, frequency, dynamic bearing capacity factors ( $N_c$ ,  $N_q$  and  $N_r$ ), and the aspect ratio of the structures .

**(Puri and Parakash , 2013 and 2014)** were conducted series of researches to evaluate and develop an accurate estimation of shallow foundation settlement during earthquake. The focusing of these researches was to determine the shear strain that produce in the soil due to seismic loading so as to get the volumetric strain because they depend on assumption that the shear strain is equal to volumetric strain at constant volume loading case. From previous researches the settlement of soil deposit equal to volumetric strain multiplying by the deposit thickness. They commented that the total settlement is equal to the summation of volumetric change in the soil due to earthquake and the settlement due to additional loading from existing structures. This additional loading was caused a reduction in shear modulus of the soil .

Due to discontinuities in soil skeleton, change in PWP during earthquake, and difference in acceleration amount there were many empirical formula, charts, and relationships were developed by many researchers for special soil condition or specific assumptions, thus the authors commented and recommended to execute more research so as to reach to a reliable settlement formula during earthquake and due to liquefaction of the supported soil. The researchers submitted good preview on soil settlement approaches.

**(Tiznado and paillao , 2014)** conducted a parametric comparison study and analysis by using different approaches so as to predict the seismic bearing capacity of shallow strip foundations. A limit equilibrium and limit analysis methods were depended in the analysis of foundation behavior during earthquake. The main results and findings from this study can be summarized as follow:

The bearing capacity of the soil is inversely proportion to the earthquake acceleration magnitude; they cited that seismic bearing capacity will decrease sharply with increasing the acceleration of the earthquake which causes rapid failure in shallow footing structures.

The well know concept of increasing the seismic bearing capacity of shallow footing by a percent up to 33% from static value is not adequate or not correct, especially at granular soils. They commented that the increasing of seismic bearing capacity makes the foundation at critical condition during earthquake and became unsafe due to the probability of liquefaction triggering and the vulnerability of the soil to densification during earthquake events.

**(Chowdhury and Dasgupta , 2016)** developed a mathematical model to simulate and analyze soil bearing capacity during seismic loading. Their findings were compatible with **(Tiznado and Paillao , 2014)** about the caution on the increasing of seismic bearing capacity especially if the underlying bed rock at shallow depth .



(Lu, 2017) was developed a practical and simple estimation for shallow foundation settlement. The researcher conducted and executed centrifuge tests, numerical and back analysis, and make calibration and verification to the concluded equations and results . (Meyerhof's formula ,1965) settlement equation was depended as reference equation.

$$S(m) = C_W \cdot C_D \cdot \frac{0.00284 q}{N} \cdot \left(\frac{B}{B+0.33}\right)^2 \dots\dots\dots (2)$$

Lu introduced new parameters which represent soil liquefaction resistance (NLR) during earthquake instead of N value in original formula of Meyerhof. The value of (NLR) was determined by using back analysis then a new chart was proposed which related the relative density of the soil (RD %) and (NLR) at different contact soil pressure and different acceleration levels.

$$S(m) = C_D \cdot \frac{q}{N_{LR}} \cdot \left(\frac{B}{B+0.33}\right)^2 \dots\dots\dots (3)$$

The author was examined and applied the proposed equation and charts on many cases that listed in literature and he found good accuracy in settlement prediction with field investigation and observation especially for the shallow foundation at liquefiable soil .

There are many other researches that discussed, analyzed, evaluated, and/or suggested prediction approaches to the bearing capacity and settlement of shallow foundation on the soil that subjected to earthquake and susceptible to liquefaction. Most of these researches are follow the same methods and approaches that explained in above review paragraphs or it depend on field tests such as SPT and CPT then relate the field results with the same approaches as discussed previously.

(Conti ,2018) derived and presented a comprehensive formula for computation of bearing capacity strip and shallow footings during earthquake on cohesive-frictional soils as well as to purely cohesive soils. His assumptions were applied by reducing the vertical bearing capacity coefficients in Terzaghi equation and introduce the effect of inertia forces on calculating the bearing capacity of the soil. The proposed new equation had an acceptable accuracy when it was compared with other approaches to check its reliability in design practice. The effects and changes in soil behavior and skeleton, during liquefaction triggering and liquefaction mitigation processes, on the design formula and soil mechanics problems of the foundation soils must be introduced in all calculations of soil bearing capacity, settlement, and stiffness to understand and expect the soil behavior.

In the present study, the above effects are introduced in a suggested modified formula for soil bearing capacity and settlement calculation.

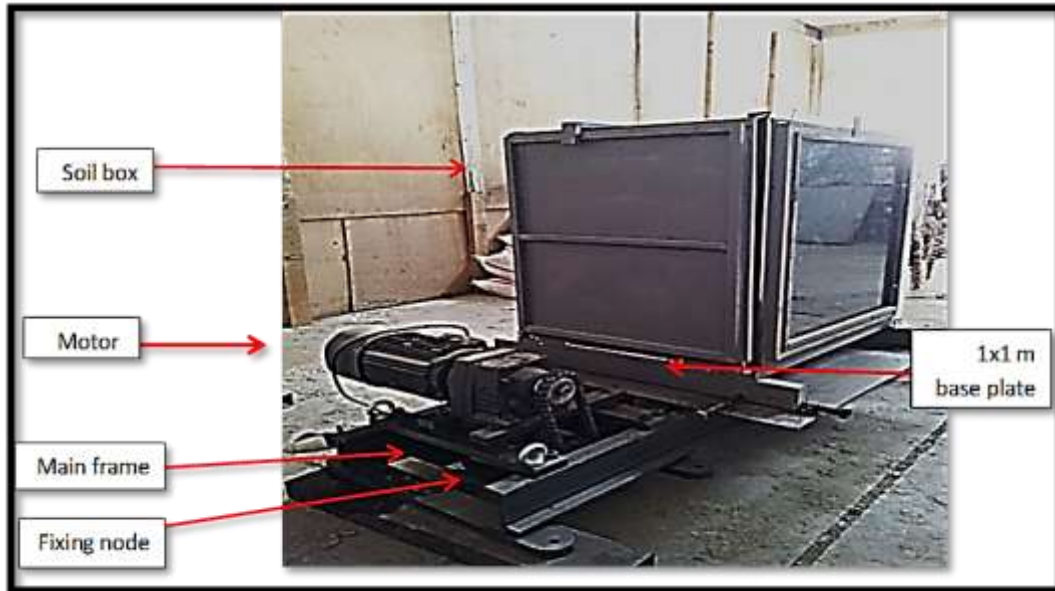
**3. EXPERIMENTAL WORK**

The measurements of seismic settlement during an earthquake is simulated by instrumented shaking table test for the soil layering before and after improvement, see Fig.1 (a) & (b). The liquefiable soil considered in this study is poorly graded sand with relative density of 33%. The soil was improved by Permeation grout using cement kiln dust (CKD) and Bentonite slurries. The grouting process was started from bottom to top by gradual steps with uniform injection process and very low injection pressure (less than 0.05 bars), using grouting machine connected to air pressure compressor to permit to the grouting material to pumping through pumping hose, depending on the depth of the injection and overburden pressure of the soil.

The correct selection of the acceleration magnitude will prevent any undesirable or unexpected failure. Therefore, the magnitude of design acceleration must be taken at foundation level, that producing from the transfer of acceleration amplitude from the source. The comparison between acceleration values at different levels in the shaking table test shows the effect of foundation level



on its behavior during shaking. The acceleration at the foundation level will become larger than its value at the source due to the effect of inertia mass motion, loose soil strata, generation of PWP and variation of stress states. **Fig. 2** presents the variation of acceleration with the depth of soil. It is clear that when the acceleration at hard strata is 0.2g (1Hz) the resulting surface acceleration at foundation level become more than 0.35g.



**Figure 1. (a)** Plate of shaking table device.

When saturated soil exposed to an earthquake, the pore water pressure will buildup and liquefaction may take place in a few seconds as shown in **Fig. 3**. This effect will result in a decrease in bearing capacity of the soil. Therefore, it is proposed to include the effect of pore water pressure in the determination of soil settlement when subjected to seismic loading.

It is important to note that the simplified approach proposed by (**Ritchard et al ,1993**) is derived to estimate settlement for non-liquefied soils. This may explain the divergence between experimental and the simplified approach, since the settlement measured experimentally for liquefied soil post liquefaction. Also, at mitigated soil the estimation of settlement according to the same formula required a modification to adjust the settlement magnitude. Settlement formula did not take into account the soil density, degree of saturation, generation of PWP, and reduction in effective stress during shaking.

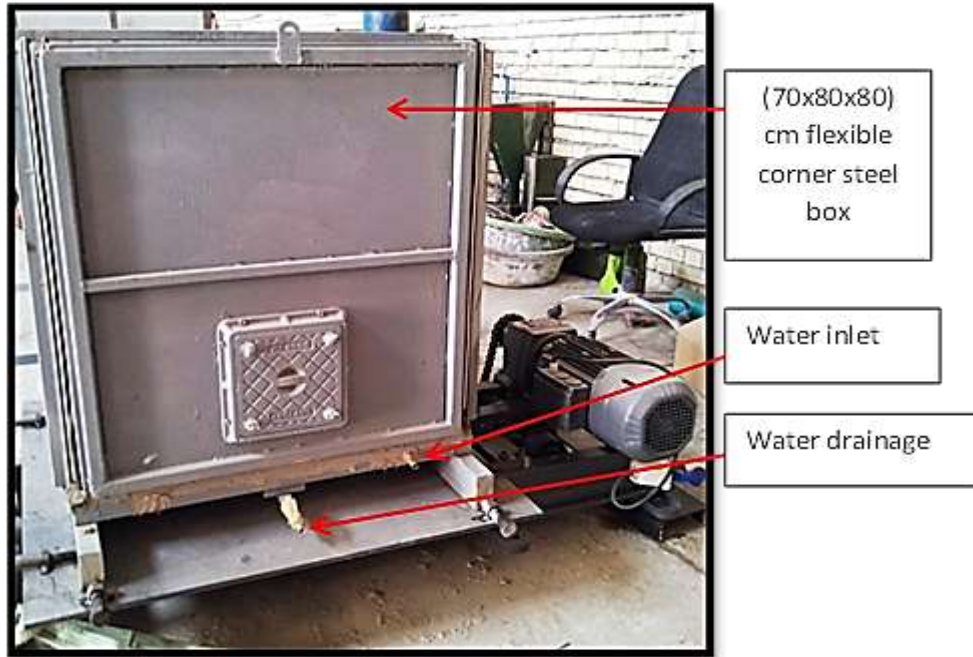
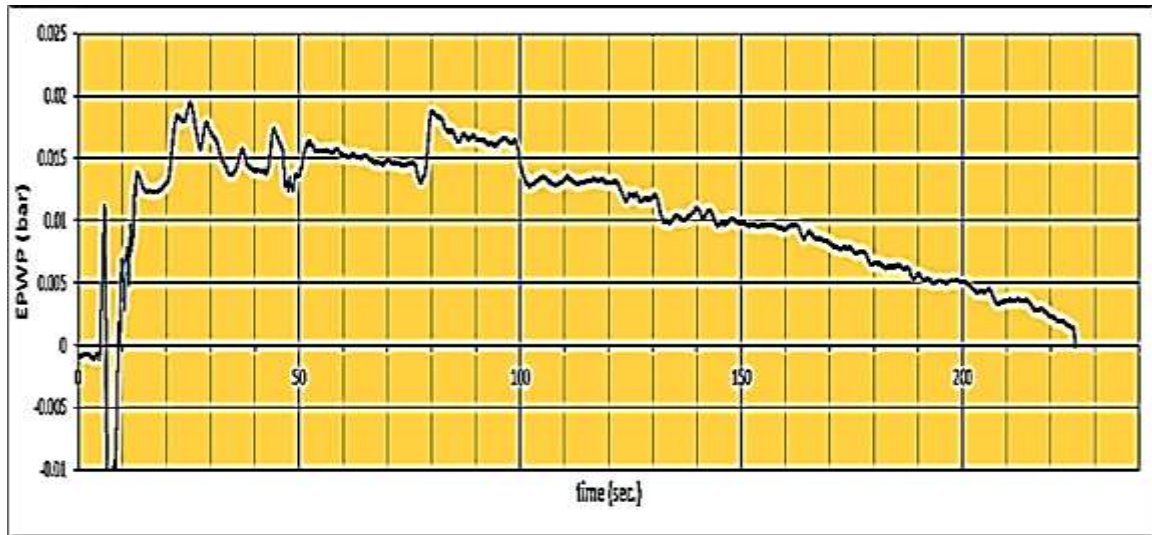


Figure 1. (b) Plate of shaking table device.



Figure 2. Acceleration amplitude distribution through soil column at saturation state for different frequencies.



**Figure 3.** Generation of PWP (bar) Vs time (sec.) at top layer of saturated soil model.

**4.THE SUGGESTED MODIFIED FORMULA FOR SEISMIC SETTLEMENT**

Based on the measured settlement values from shaking table test on foundation resting on improved and unimproved soil, a statistical analysis has been performed to obtain a modified formula for settlement evaluation. The modified formula, that suggested using statistical analysis by SPSS software, takes the effect of soil density and pore water pressure generation during an earthquake in consideration, See equations (4) and (5).

**For frequency amplitude ≤ 0.75**

$$S_{Eqm} = S_{Eq} * \left(\frac{\gamma_{soil}}{\gamma_{new}}\right)^a * \left(\frac{b}{(c-r_u d)}\right) \dots\dots\dots (4) \quad \text{for } (r_u < 0.90)$$

Where a, b, c, and d: are an empirical coefficient from statistical analysis by SPSS software and it equal to: (58.78, -1.85, 1, and -0.133 respectively) the regression coefficient (R2 = 0.95).

**For frequency amplitude > 0.75**

The empirical coefficients (a, b, c, and d) become as follow: (-35.1, -321.6, -468.8, and -3.83 respectively) the regression coefficient (R2 = 0.86).

Where:  $\gamma_{new}$  is the new soil density after densification or improvement.

A good convergence between modified formula and experimental measurement noticed for the cases of non-liquefaction. In case of  $r_u$  (0.9-1) there are additional formula can be introduced which cover the effect of pore water pressure generation and the reduction in effective stress. This formula can be written as follow:

$$S_{Eqm} = S_{Eq} * \left(\frac{\gamma_{soil}}{\gamma_{new}}\right)^e * \left(\frac{1}{r_u}\right)^f \dots\dots\dots (5)$$

Where e, is an empirical coefficient from statistical analysis which equal to 1.5 and  $f = (\gamma_{soil} / (1 - (\gamma_{new} - \gamma_{soil})) / 100)$ . The regression coefficient of this formula is (R2 = 0.89).

**Fig. 4** presents the settlement of the foundation, due to shaking before soil improvement, recorded experimentally and calculated by using original Ritchard, modified formula and Lu formula.

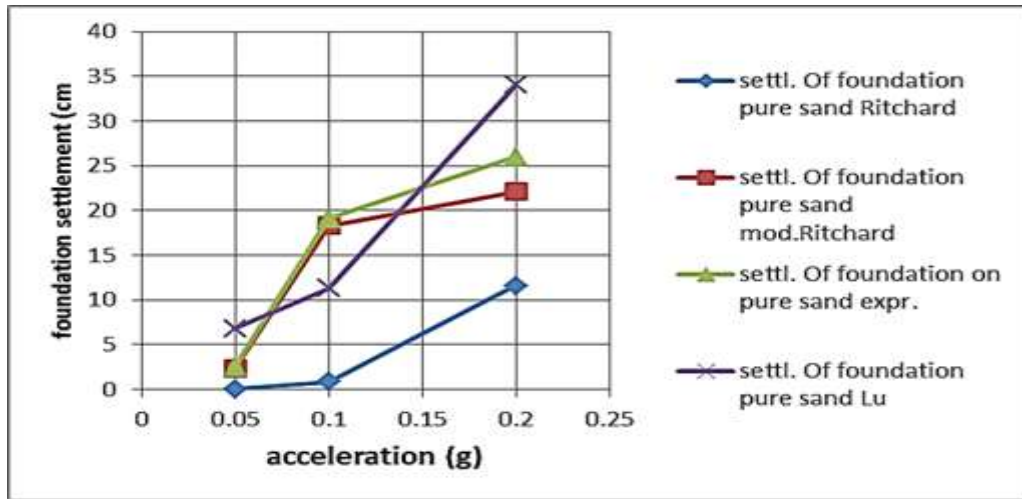
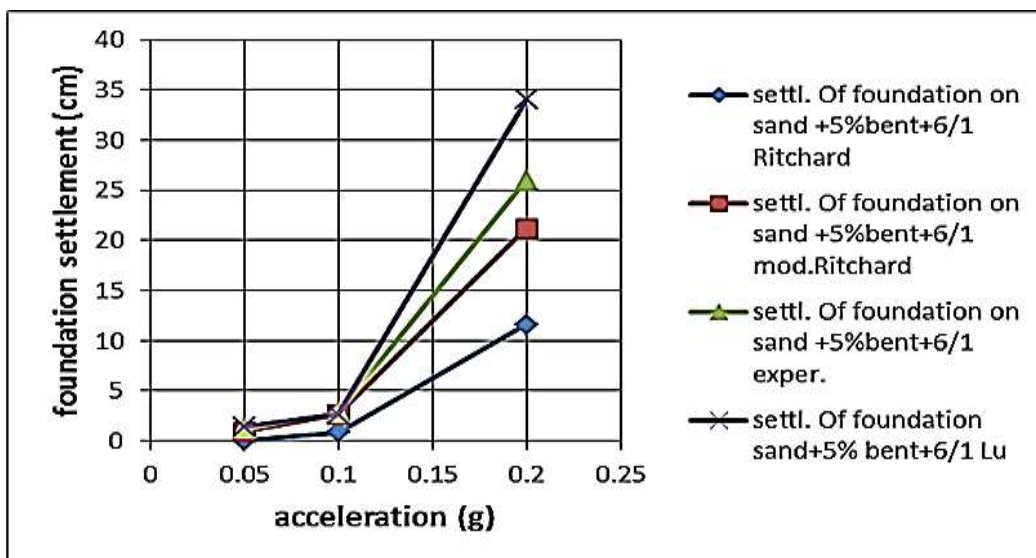


Figure 4. Relationship between settlement of foundation and acceleration on saturated pure sand.

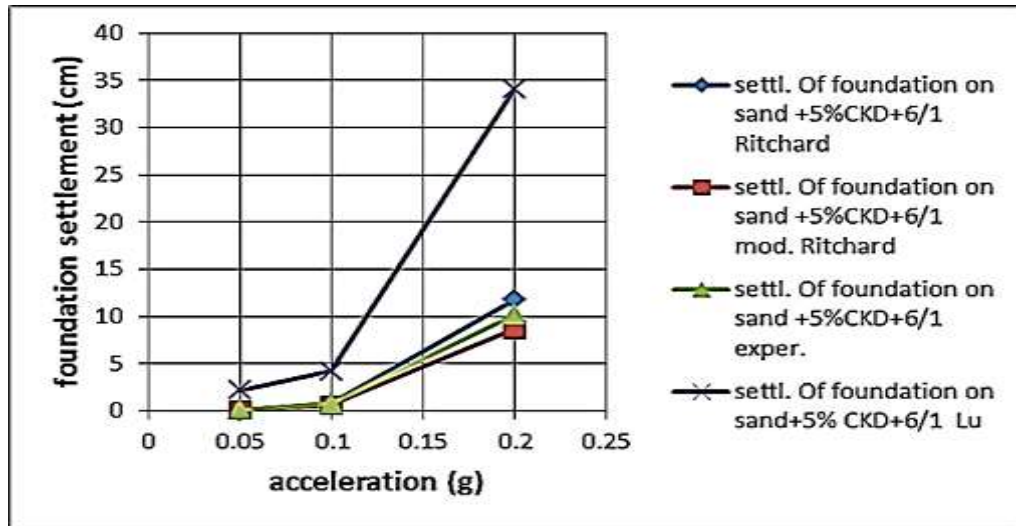
Fig. 5 presents the settlement of the foundation during shaking after soil improvement using permeation grout of CKD and bentonite slurries (each one prepared at 5% of material and 6/1 dilution ratio). It is shown a comparison among settlement values, at different accelerations, measured experimentally and that determined using Ritchard formula, Lu formula, and Ritchards formula that modified in the current study.

It is observed that the original Richards formula is suitable for high acceleration levels without probability of liquefaction triggering. For (Lu, 2017) formula it is clear that this formula is suitable and more accurate for low frequency shaking but in general it gives an over estimation for the settlement especially at high acceleration levels. Also, the effect of motion parameters is not introducing in LU formula as a control agent which may effect on the approaching of the result from experimental and field data.



(a)





(b)

Figure 5. (a) & (b) Relationship between settlement of foundation and acceleration on saturated sand improved by: (a) 5% Bentonite + 6/1 dilution percent (b) 5% CKD + 6/1 dilution percent.

5. CONCLUSIONS

Empirical and mathematical approaches were adopted in the present study, in the aim of simulate, represent, evaluate, and modify the existing formula of seismic settlement for shallow foundation at ordinary soil conditions to be suitable, give accurate, and compatible outcomes under earthquake loading, liquefaction triggering, and mitigation conditions.

A modified formula for the prediction and calculation of shallow foundation settlement for the soil susceptible to liquefaction and improved soil was established. This formula takes into consideration the acceleration amplitude level of the site, soil characteristics, generation of PWP. The modified formula showed close results and compatible outcomes with the experimental results and other literature data.

NOMENCLATURE

- CKD = cement kiln dust..
- $r_u$  = PWP ratio.
- PWP = pore water pressure (bar, kPa).
- $\gamma$  = soil unit weight ( $kN/m^3$ ).
- f = frequency of the shaking table (Hz).

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