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# Settlement of Shallow Foundation in Dry Sand Under an Earthquake

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## HIGHLIGHTS

- A triple-axis shaking table is manufactured to simulate the history of earthquakes.
- A settlement in two directions shaking is more than it in one direction shaking.
- A freedom degree has an impact on foundation settlement and is proportional to it.
- Local magnitude & max. acceleration increases settlement for all directional shaking.
- Under shaking, soil particles are re-orientated, and voids in the soil are reduced.

## ARTICLE INFO

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## ABSTRACT

Seismically induced settlement of buildings with shallow foundations resting on dry sand soils has resulted in severe damage in recent earthquakes. A multi-degree of freedom shaking table and a fixed container were manufactured and used to study the foundation settlement. Series of shaking experiments on the shallow foundation situated in a center of the container and atop of a dry sandy soil has been performed to identify the mechanisms involved to calculate the foundation settlement induced by earthquake shaking. In this research, the important factors are identified, including shaking intensity, the soil relative density, the degree of freedom and the building's weight. Two relative densities (55 % and 80%) are used and three local magnitudes of earthquakes (5.8, 6.4 and 7.2) (Anza, Jalisco, and Guerrero) respectively with one and two degrees of freedom. The results of the shaking indicated that shallow foundation settlement on the dry sand increases with the increase of the local magnitude of earthquakes and maximum acceleration. In the case of Anza, the percentage decrease in the settlement between the relative density of 55% and 80% for systems (x and xy) are (47% and 42%) respectively. While in the case of Jalisco and Guerrero, the percentage of decreases in their settlement and for the same systems is (11% and 57%), (36% and 36%) respectively. The degree of freedom has an impact on the foundation settlement; it is proportional to the degree of freedom. Also, the results show that the settlement decreases when the relative density of sand increases.

## 1. Introduction

For any land-based structure, the foundation is very important and must be strong to support the entire structure. For the foundation to be strong, the soil underneath it plays a very critical role. So, the soil needs to have proper knowledge about their properties and factors which affect their behavior [1]. The settlement of soil below the shallow foundation in dry sandy soil underneath the seismic loading may be major damage to most structures throughout the earthquake. On the opposite, vibration and shaking are efficient techniques for compressing cohesionless soil and can reduce the settlement of soil.

The acceleration of the ground surface is due to various seismic waves generated by the fault rupture. There are two basic forms of seismic waves: body waves and surface waves [2]. P and S waves are each known as body waves as a result they will pass through the interior of the earth. During several earthquakes, the waves may be increased the settlement, tilt and caused a reduction in the bearing capacity of shallow foundations due to seismic loading. The foundation must be safe for the static and dynamic loads imposed by the earthquakes.

Day, [3] stated that soil densification or volumetric compression is the type of settlement that occurs due to the earthquake-induced ground shaking and causes the soil particles to compress together. Non cemented cohesionless soils, like dry and loose sands, are susceptible to this type of settlement. A volumetric compression can result during a great amount of ground surface settlement. A remarkable case of ground vibrations was described from the 1964 Alaskan earthquake that caused 0.8 m (2.6 ft) of sediment settlement [4].

The settlement of dry sands throughout the earthquakes under below one-directional loading within the laboratory was firstly studied in 1971 and 1972 [5,6]. Pyke et al. [7] expanded the action by Silver and Seed and inspected the effects of multidirectional shaking on the sand's settlement using a shake table. The empirical results showed that the dry sands settlement below multi directional shaking can be larger than that gained in single directional loading tests. Tokimatsu and



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Seed [8]advanced a procedure for estimating dry sand settlements because of earthquake shaking and recommended standard practice. They showed that the elementary factors controlling earthquake-induced settlement are the cyclic shear strain for dry or partially saturated sands and the cyclic stress ratio for saturated sands with pore pressure generation. Knappett et al., [9] studied the impact of earthquake magnitude and critical failure mechanism and as expected, the increase in kh (horizontal acceleration in g) resulted in a larger final settlement as shown in Figure 1. The vertical displacement gained from centrifugal testing was studied using Nevada sand with a relative density of around 60%, the vertical displacement recorded close to the middle of the model surface was larger than that measured close to the end wall. The maximum settlement was determined to be close to adequate to 2.54 cm [10].

In this research, the shaking table is manufactured to generate earthquake motions with a vast range of magnitudes and multi directions to evaluate an earthquake-induced settlement.

## 2. Test Design and Program

Physical modeling is performed to study particular cases of the behavior of prototypes and to validate theoretical and/or empirical hypotheses. However, most physical models will be constructed at much smaller scales than the prototype precisely because it is desired to obtain information about expected patterns of response more rapidly and with closer control over model details than would be possible with full-scale testing [11].

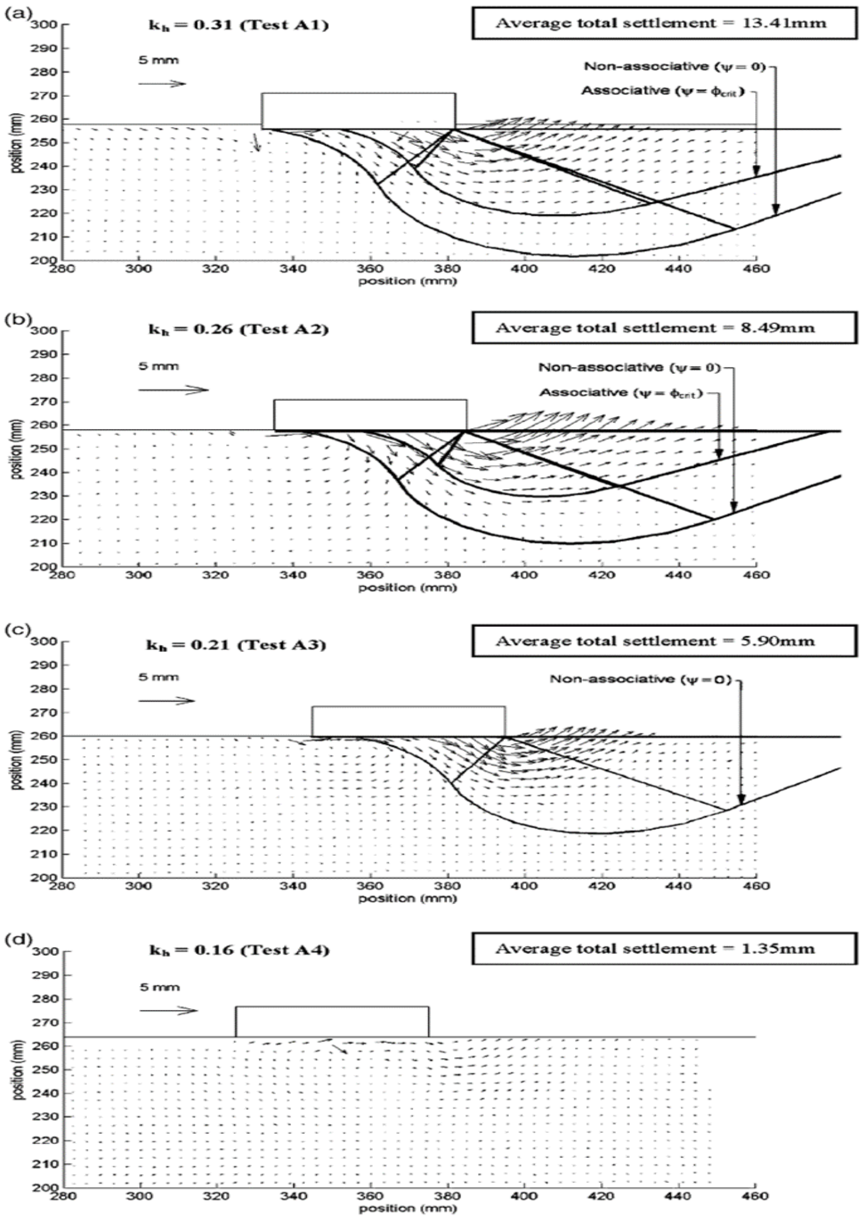


**Figure 1:** Effect of earthquake magnitude on critical failure mechanism [9]

A triple-axis shaking table machine is manufactured to simulate the history of three different earthquakes and to study the behavior of dry sandy soil supported a small-scale shallow foundation. The manufactured shaking table is divided into several main parts such as steel frame, Ball joint and Pneumatic cylinder, Air compressor and Controller and data gathering system shown in Figure 2. In this research, two directions of shaking X and Y directions are used to study the settlement in dry sand under different earthquake histories. A fixed container of (70 × 70 × 80 χμ) was used. The Polyethylene foam with 20 mm thickness is fixed in internal faces to reduce the wave reflector during testing. The scale factor (λ) for the current study equal to 300 is enough to simulate the prototype parameter of the scale model for all parameters considered at reasonable foundation dimensions in a full scale.

The acceleration is modeled by a factor of unity and linear dimensions are syndicated by the scale factor of 1:1/ λ (prototype: model). The current dimensions of the foundation used are 75 × 75 mm embedment at depth (Df) equals zero. The load current capacity is obtained according to the criterion stated by [12] [10 % from width footing]. This load represents the ultimate load and equals (0.38 kN) and the factor of safety is used to find allowable load is 3 (0.126 kN). This ratio is a maximum allowable settlement; the load-settlement curve for a relative density of 55% is shown in Figure 3.

The sand is placed in the rigid container as layers with 100 mm thickness for each and dynamic compacted using manufactured hammer reaching to the required density. After that, the foundation is laid on the surface of the soil and in the center of the container as shown in Figure 4. Then, the device is connected to the Pc where it starts to work based on the seismic wave input as well as the settlement sensor is measured at the same time. The settlement sensor is a laser time flight VL53L0X sensor shown in Figure 5. The VL53L0X is a sensor that allows distance measurements to be made by measuring the time of a laser flight (TOF).

Different real earthquake acceleration history data are adopted Anza, Near the Coast of Jalisco 2003 and Guerrero 2001. Table 1 presents the information of the used earthquake data. Furthermore, a set of modified acceleration histories of Anza earthquake are implemented by multiplying it with an acceleration factor (ACF) to focus on various acceleration amplitudes for the same acceleration history characteristic of the local and modified earthquakes (Anza). Figure 6 shows the case studied of acceleration history.

The used soil is classified as poorly graded sand with a symbol (SP) according to the Unified Soil Classification System (USCS). Table 7 and Figure 6 depict the grain size distribution and physical properties of used sand.

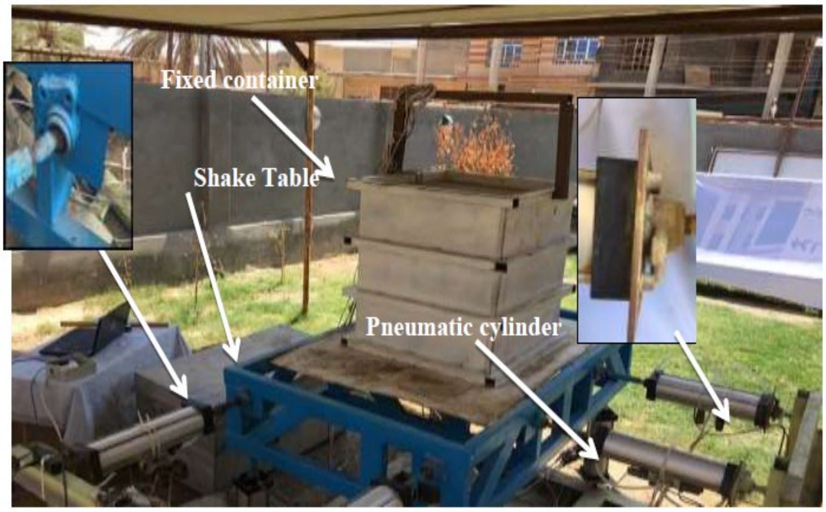


**Figure 2:** Six degrees of freedom shaking table

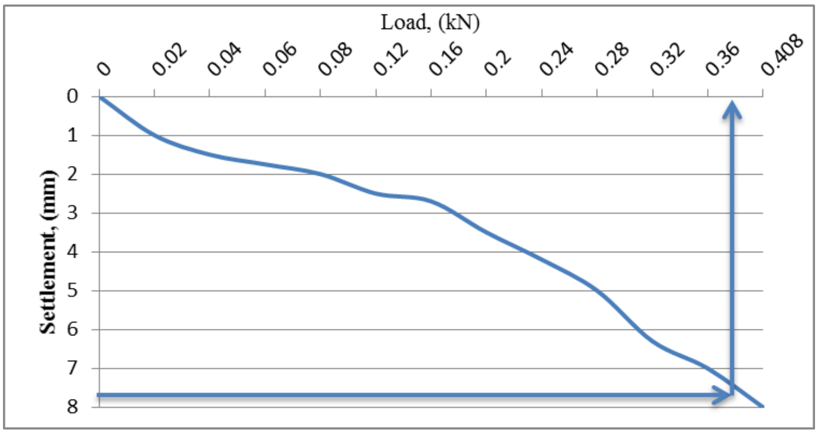


**Figure 3:** curve of the load-settlement for a relative density 55%

**Figure 4:** The foundation and mass placed in center of container.

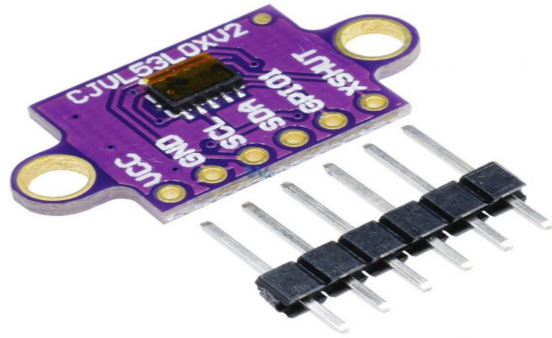


**Figure 5:** VL53L0X Sensors (Settlement Sensor)

**Table 1:** Information of the Earthquake Data

| Earthquake | Anza | Jalisco | Guerrero |
|---|---|---|---|
| Region | California | Mexico | Mexico |
| Magnitude (ML) | 5.8 | 6.4 | 7.2 |
| Modified Mercalli intensity | VII–VIII | VIII – IX | IX–X |
| Epicenter depth (km) | 136.7 | 167.0 | 41.3 |
| Shake duration (sec) | 58 | 146 | 110 |
| Maximum Acceleration (g) | 0.1 | 0.29 | 0.4 |
| Reference | www.strongmotion center.org | www.strongmotion center.org | www.strongmotion center.org |

**Table 2:** Physical properties of sandy soil used for testing

| Physical properties | Value | | Specification |
|---|---|---|---|
| Specific gravity, $Gs$ | 2.66 | | ASTM D 854 [13] |
| D10 (mm) | 0.12 | | |
| D30 (mm) | 0.17 | | |
| D60 (mm) | 0.23 | | ASTM D 422 and ASTM D 2487-[14] |
| Coefficient of uniformity (Cu) | 1.91 | | |
| Coefficient of curvature (Cc) | 1.04 | | |
| Soil classification (USCS) | SP | | |
| Maximum void ratio | 0.959 | | ------ |
| Minimum void ratio | 0.535 | | ----- |
| Maximum dry unit weight (kN/m3) | 17 | | ASTM D 4253[15] |
| Minimum dry unit weight (kN/m3) | 13.32 | | ASTM D 4254 [16] |
| Angle of internal friction, (deg.) | R.D = 55% | R.D = 80% | ASTM D 3080 [17] |
| | 30.7 | 36.2 | |

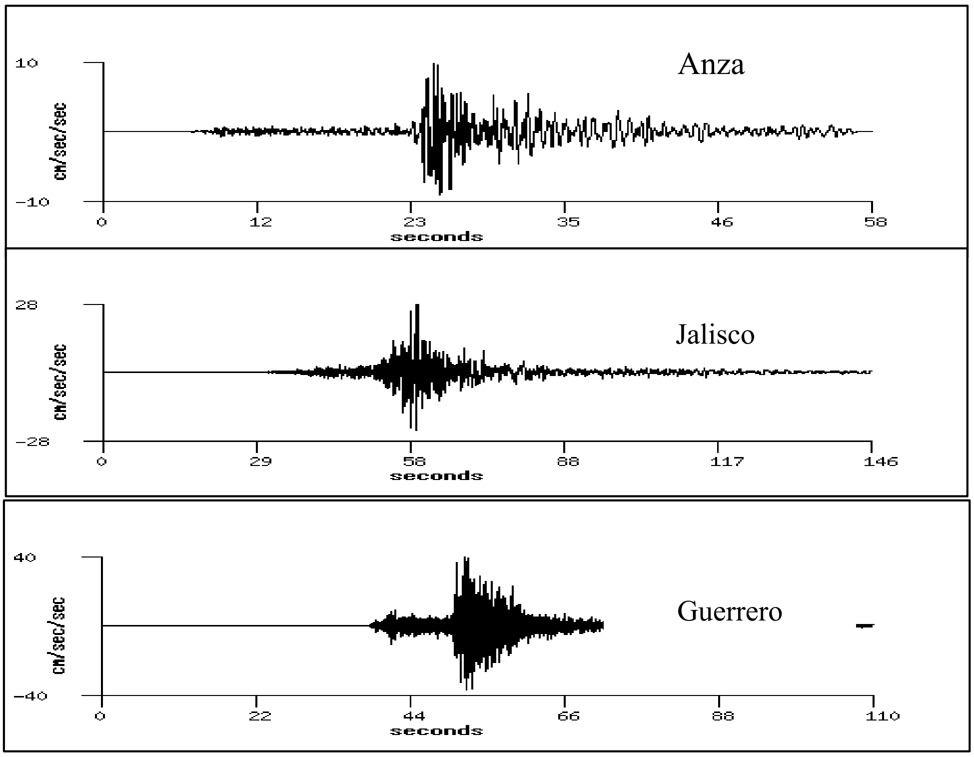


**Figure 6:** acceleration histories of the used earthquakes

**Table 3:** Physical properties of sandy soil used for testing

| Physical properties | Value | | Specification |
|---|---|---|---|
| Specific gravity, $Gs$ | 2.66 | | ASTM D 854 [13] |
| D10 (mm) | 0.12 | | |
| D30 (mm) | 0.17 | | |
| D60 (mm) | 0.23 | | ASTM D 422 and ASTM D 2487-[14] |
| Coefficient of uniformity (Cu) | 1.91 | | |
| Coefficient of curvature (Cc) | 1.04 | | |
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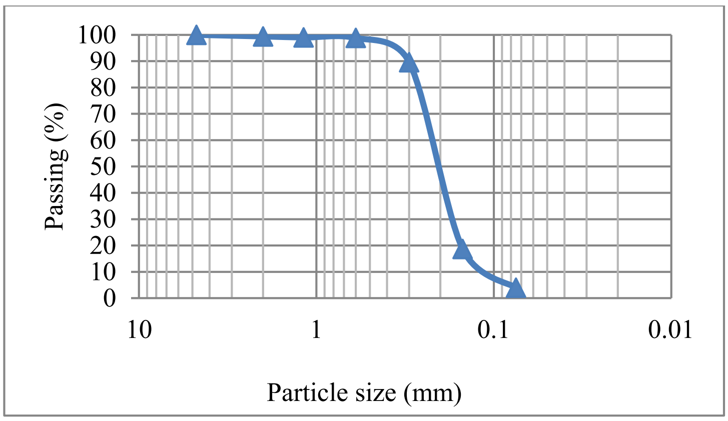


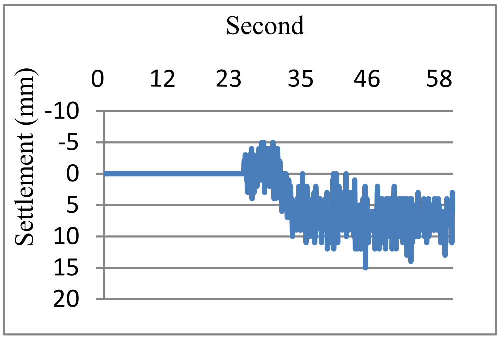

**Figure 7:** Grain size distribution curve of the sand used

## 3. Test Result

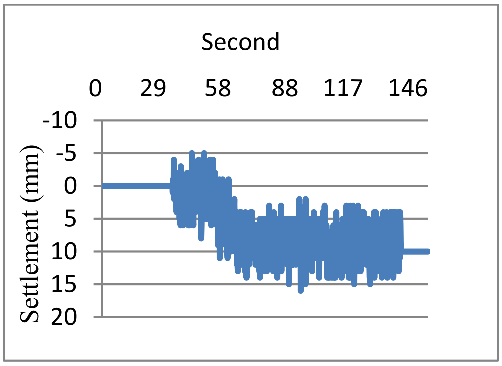
### 3.1 Effect of Settlement by Relative Density

To study the effect of the relative density of dry sand on the foundation settlement, several tests were done and used different wave directions. Two relative densities are used (Dr = 55% and 80%)that present the sand in (medium and dense) states, respectively. The settlement records in Anza, Jalisco and Guerrero wave motions are illustrated in Figure 8. The settlement occurred at implementing Anza case in x-direction on dense and medium sandy soil models does not exceed the allowable settlement due to the low magnitude and low maximum acceleration in this case while in the x-y directions, the settlement exceeded the allowable settlement because the waves generated in two directions have double effects on the foundation.

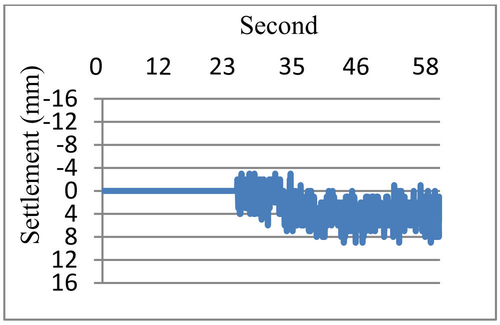
Figures 9 to 11 show the effect of the relative density on the foundation settlement. At a relative density is 80%, the final settlement is lower than the settlement in a relative density of 55% in different earthquake histories and different directions. This is attributed to that; a low-density soil contains more voids and as a result of the earthquake, the soil particles under shaking begin to reorientate and close together and this process reduces the voids in the soil structure and the soil will be settled. The settlement in the x-y system for Dr = 80% is greater than the settlement in the x system for Dr = 55% although the settlement in medium-density is greater than the dense density. These results showed that the settlement under multidirectional shaking in dry sandy soil can be larger than that gained in one-directional loading tests and this is identical to findings of [7].



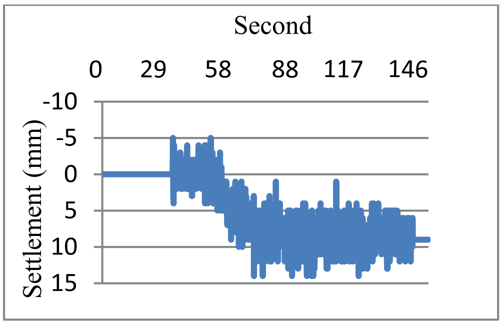

A: Settlement for Anza case Dr = 55% in X direction



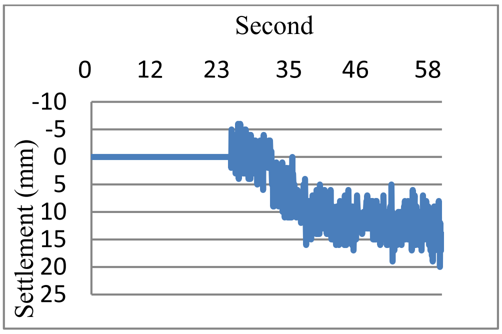

A: Settlement for Jalisco case Dr = 55% in X direction



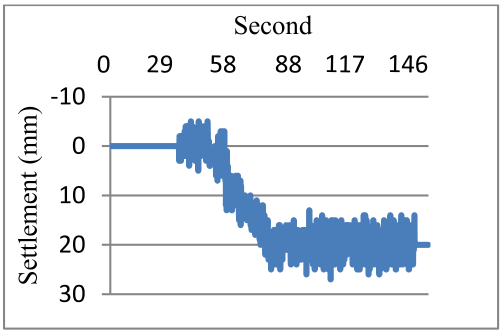

B: Settlement for Anza case Dr = 80% in X direction




B: Settlement for Jalisco case Dr = 80% in X direction

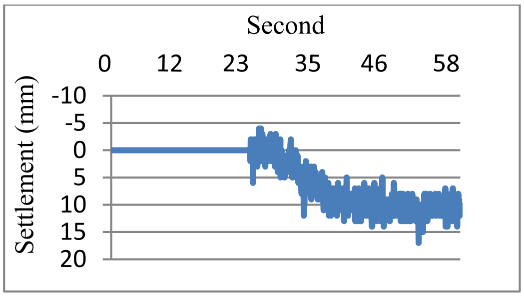



C: Settlement for Anza case Dr = 55% in X-Y direction

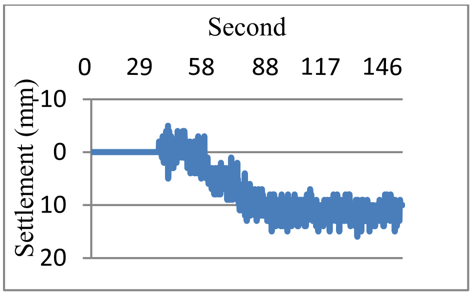



C: Settlement for Jalisco case Dr = 55% in X-Y direction

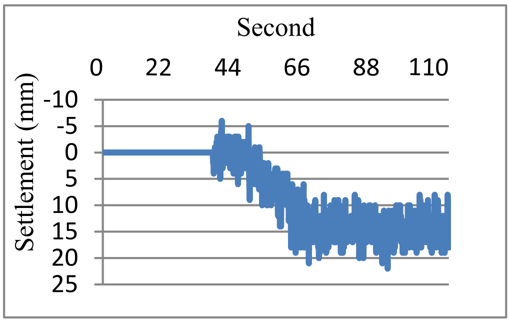
**Figure 8:** Settlement with time for different case



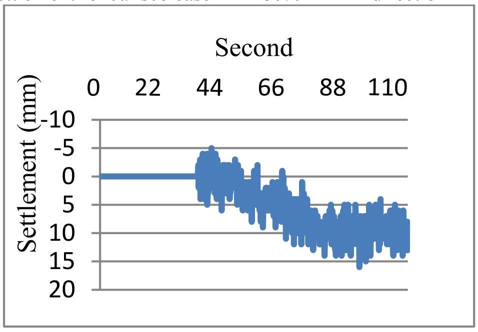

D: Settlement for Anza case Dr = 80% in X-Y direction



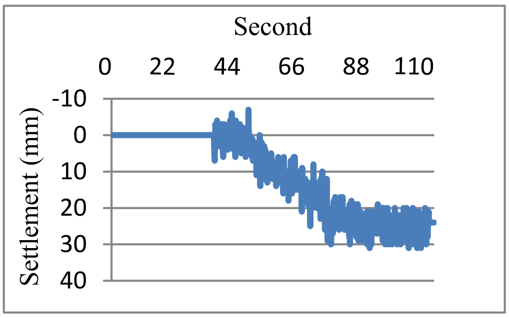

D: Settlement for Jalisco case Dr = 80% in X-Y direction



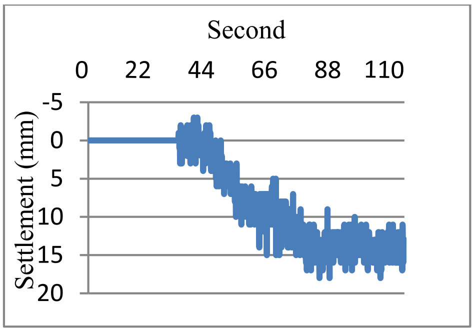

A: Settlement for Guerrero case Dr = 55% in X direction




B: Settlement for Guerrero case Dr = 80% in X direction




C: Settlement for Guerrero case Dr = 55% in X-Y direction




D: Settlement for Guerrero case Dr = 80% in X-Y direction

Figure 8: Continuied

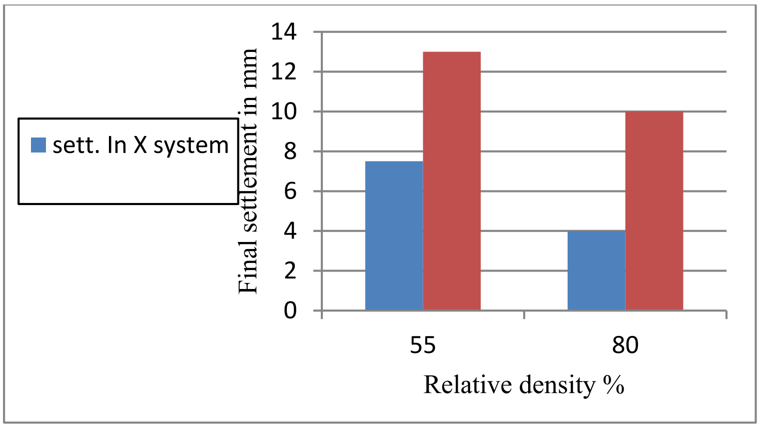



**Figure 9:** Final Settlement with different relative density for Anza case

## 3.2 Effect the Magnitude of Earthquake on Footing Settlement

The earthquake magnitude, waveform, maximum acceleration, and duration of ground shaking affect the final settlement. The settlement in two directions shaking is greater than the settlement in the shaking in one direction for different earthquake histories and relative densities. The settlement increases when the local magnitude and maximum acceleration increased for all directions systems. In the Guerrero case, the settlement is greater than other cases and the settlement in the Jalisco case is greater than the Anza case as clarified in Figures 12 and 13. These results are due to the high magnitude and maximum acceleration in the case of Guerrero comparing with the other cases, although the time in the case of Guerrero is less than the time in the case of Jalisco. These results agreed with [9] experiences, who stated that (a larger total settlement occurred at maximum acceleration). Also,[18] found that the amplitude of acceleration and frequency domain has led to a considerable effect on settlement and lateral displacement in the z-direction.

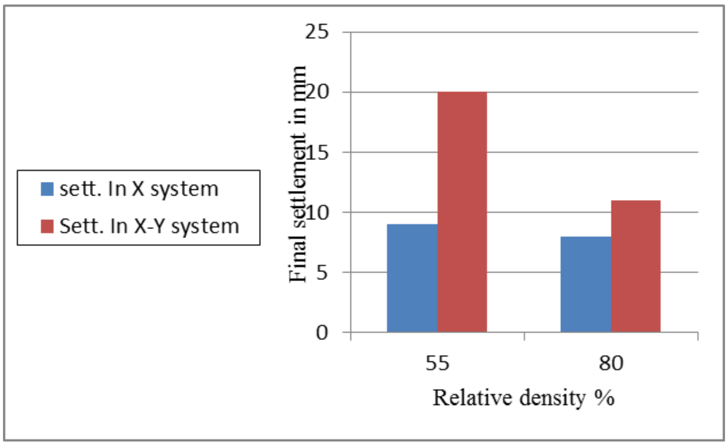



**Figure 10:** Final Settlement with different relative density for Jalisco

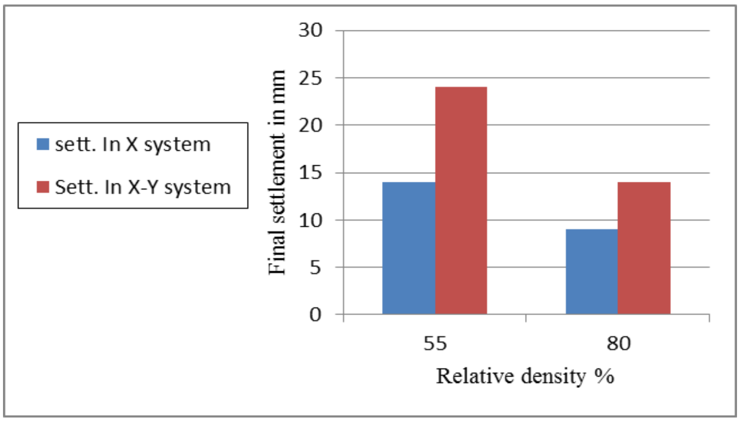



**Figure 11:** Final Settlement with different relative density for GuerreroCase

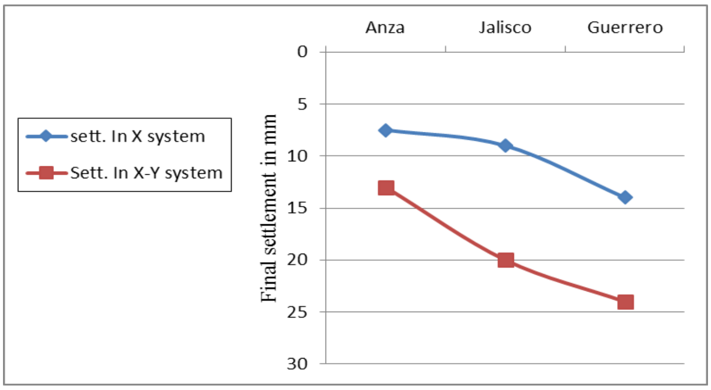



**Figure 12:** Final Settlement with different Acceleration history for relative density 55%

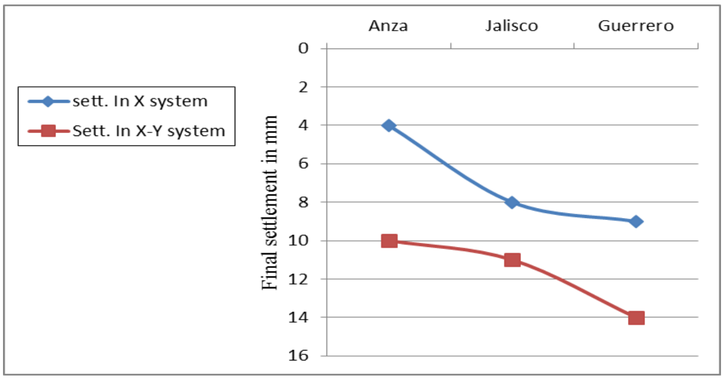



**Figure 13:** Final Settlement with different Acceleration history for relative density 80%

## 4. Conclusions

In this study, 12 typical tests are performed on the foundation model resting on dense, and medium sandy soils. Different criteria are studied involving soil conditions, earthquake history and waves of directions. Numerous conclusions have been drawn through this research as follows:

1) For all types of earthquake waves and in all the direction, the final settlement in the medium density is greater than the final settlement in the dense sand.
2) A dry sand settlement under a multidirectional shaking is greater than that obtained in unidirectional loading tests.
3) Increasing the local magnitude and the maximum acceleration leads to the increase in the settlement under multidirectional or single directional shaking tests.
4) In the case of Anza, the percentage decrease in the settlement between the relative density of 55% and 80% for systems (x and xy) are (47% and 42%) respectively, while in the case of Jalisco and Guerrero, the percentage of decreases in their settlement and for the same systems is (11% and 57%) (36% and 36%) respectively.
5) In the (x and xy) systems, the percentage increase in the settlement between the case of Jalisco and Anza is 20% and 134% for the relative density of 55% and for the relative density of 80% is 100% and 72%respectively while between the case of Guerrero and Anza the settlement increased is 86% and 266%for the relative density of 55% and 125% and 302%for the relative density of 80% additionally between the case of Guerrero and Jalisco the settlement increased is 56% and 57%for the relative density of 55% and for the relative density of 80% is 12.5% and 134%.

### Author Contribution

All authors contributed equally to this work.

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### Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author.

### Conflicts of Interest

The authors declare that there is no conflict of interest.

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