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EXPERIMENTAL STUDY OF SEISMIC RESPONSE OF THE SQUARE TUNNEL IN GRANULAR SOIL

*Omar Yaseen Almashhadany[1], Dr. Bushra Suhale Albusoda[2]

1) PhD. Student, Civil Engineering Department, University of Baghdad, Baghdad, Iraq.
2) Prof., Civil Engineering Department, University of Baghdad, Baghdad, Iraq.

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Abstract: In this study a series of shaking table tests were carried out to investigate the effect of tunnel model depth and direction of ground acceleration on the horizontal acceleration of tunnel model and soil beside it, ground surface settlement, and the dynamic earth pressure on the tunnel wall. Square tunnel model embedded in both dry and saturated soil (Karbala Sand). It subjected to three input sinusoidal motions 0.05g, 0.1g, and 0.2g. Two relative densities used, 30% for the upper layer and 70% for the lower layer. The results obtained indicate that the direction of seismic loading has significant effect on the horizontal acceleration of tunnel model. The increase of tunnel model depth lead to decrease the horizontal acceleration of tunnel model. While, the settlement of soil surface increases with an increase of tunnel model depth and ground acceleration especially at 0.2g earthquake loading. The change of direction of seismic loading leads to a small change in the settlement for dry soil. The results appear that dynamic earth pressure (DEP) was positive in dry soil and negative in saturated soil in all test. In saturated soil, the effect of direction of ground acceleration and depth of tunnel model on DEP in 0.2g is quite little.

Keywords: *Shaking table test, Direction of ground acceleration, Horizontal acceleration of tunnel, Seismic settlement, Dynamic earth pressure*

1. Introduction

The large underground structures and tunnels subjected to large damage during/after the earthquake leads to cause large deformation or even collapse of these structures. In seismic zones, tunnel structures must be designed to withstand significant seismic forces and static overburden loads. The response of tunnel subjected to seismic loading has connected to the response of surrounding soil due to inertia response and deformation of soil that controls the response of the tunnel. Therefore, main focus when studying the response of tunnel is on the soil- tunnel interaction effect of uplift force on a tunnel in liquefied soil, transverse raking deformation, mechanisms of transferring the load between the surrounding soil and tunnel, and failure mechanisms of the tunnel.
The seismic response of the underground structures has been extensively investigated through a series of numerical [9] and [11], and experimental studies [10], [12], and [14].

*Corresponding Author: omaryaseen60@yahoo.com

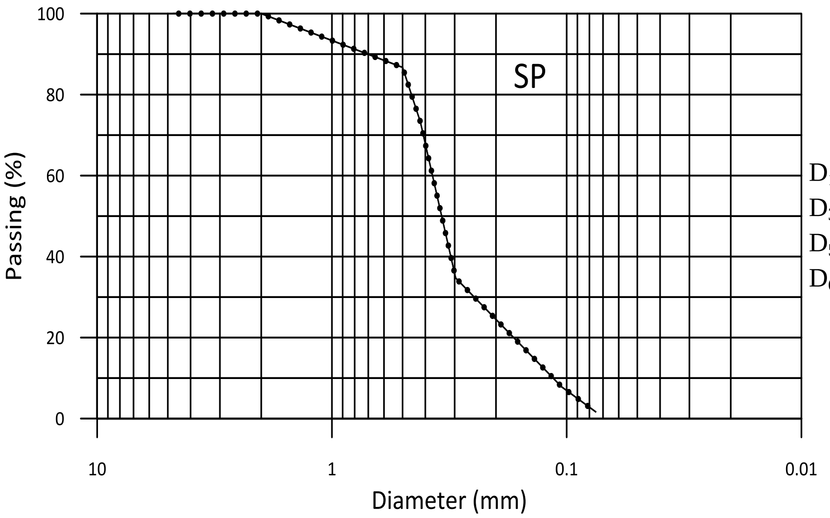
However, some seismic response researches of box-shaped tunnels being still studying, including seismic earth pressure on the side wall of the tunnel, seismic displacement above and around the structure and a complex mechanism of dynamic deforming of the tunnel during vibration.

In previous studies, all researchers have examined the response of tunnel structure under seismic loading. Their studies focused on the racking and the uplift displacement of the tunnel structure. In this study, the focus will be on studying the effect of soil saturation on the horizontal acceleration of tunnel and soil around it, the tunnel response at different depths, and the horizontal earth pressure on the tunnel side walls.

2. Experimental Programs

2.1. Geotechnical Properties of Soil

In the present study, Karbala sand has been used as model of ground. Standard tests were carried out according to ASTM standards to determine the physical and mechanical properties of sand. "Fig. 1" shows the grain size distribution of the soil [4], while the physical properties of sandy soil have been presented in Table 1.



D_{10} = 0.11 mm
D_{30} = 0.28 mm
D_{50} = 0.38 mm
D_{60} = 0.4 mm

Figure (1) Grain Size Distribution for Sand

Table 1. Soil Properties.

Index Properties	Specific Gravity	Maximum Unit Weight (KN/m^3)	Minimum Unit Weight (KN/m^3)	Angle of internal fraction (ϕ)
ASTM Standards	ASTM D854-2005 [8]	ASTM D4253-2000 [5]	ASTM D4254-2000 [6]	ASTM D3080-1998 [3]
Values	2.63	15.86	14.13	31°

2.2. *Tunnel Model*

A square plastic tunnel has been used with dimensions (25×25) mm and thickness of 1.5 mm. The length of the tunnel is 760 mm (less than the width of the steel box (800 mm)) to avoid any interaction between the tunnel and the steel box that affect the behavior of the tunnel. The two ends of the tunnel are closed by paste and silicone to prevent the entrance of soil and water inside the tunnel. Also, the tunnel ends are fixed by two-rod bolts that connected with two sides of the steel box to prevent the movement in any direction. Also, the pressure sensor has fixed on the right wall of the tunnel, see "Fig. 2".

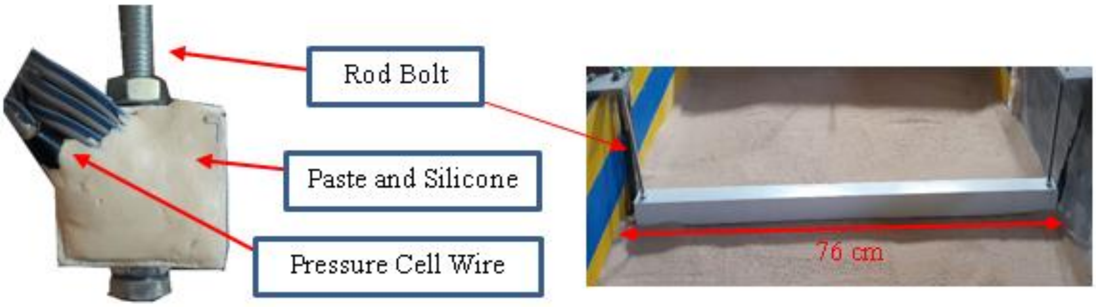


Figure (2). Tunnel Model.

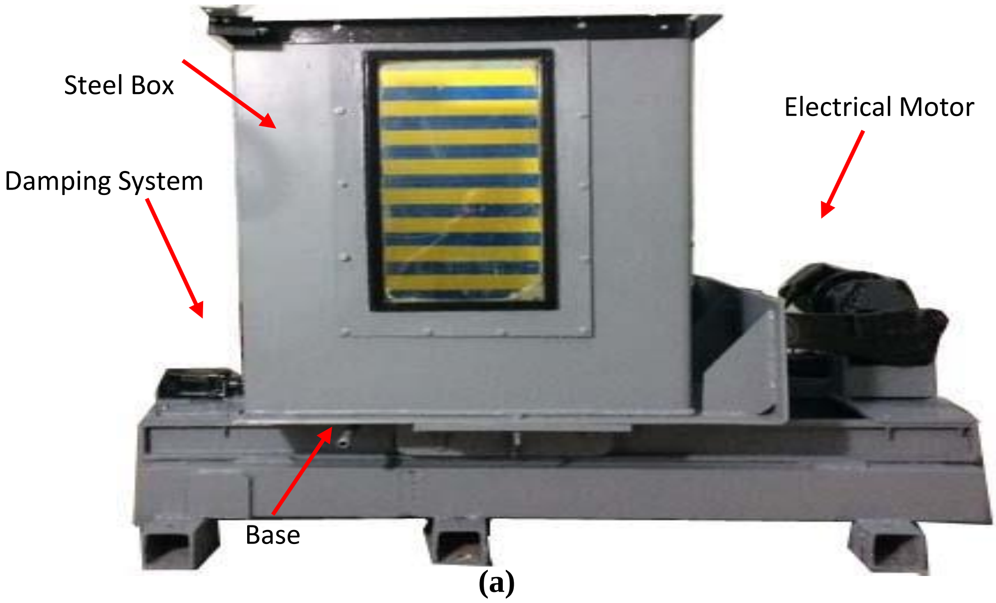
The mechanical properties of the tunnel model have determined by the tensile test according to ASTM D638- 2003 [7] specifications. The results of the test have shown Table 2.

Table 2. Mechanical Properties of the Tunnel Section.

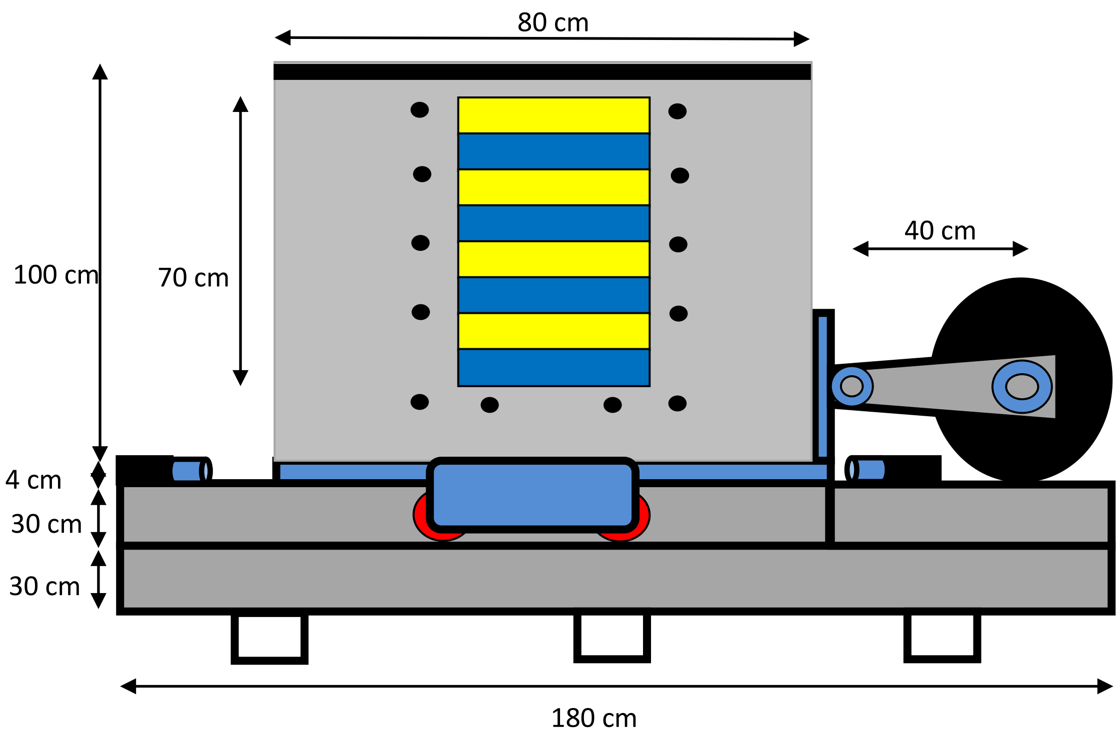
Properties	Moment of Inertia (mm^4)	Poisson's Ratio (v)	Modulus of Elasticity E (N/mm^2)
Value	2604.2	0.4	106.5

2.3. Shaking Table

A shaking table was used to study the response of tunnel structure subjected to seismic loading. The shaking table is manufactured by [2] and developed in this study. It includes three parts: a) Shaking table base and Electrical motor, b) Steel box; and c) Damping system, see "Fig. 3".



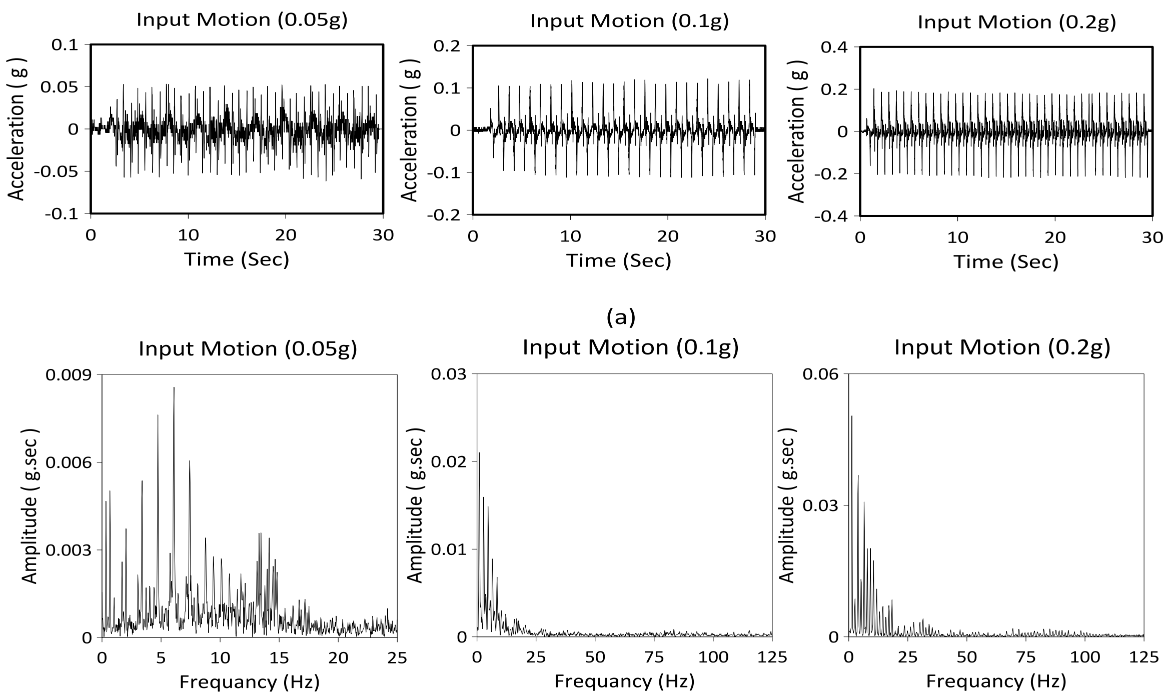
(a)



(b)

Figure (3) a) Shaking Table Setup b) Schematic Diagram of Shaking Table

The soil-tunnel models were subjected to three different types of input motion 0.05g, 0.1g and 0.2g during all tests using shaking table for 30 seconds. The input motion time histories have presented in "Fig. 4".



(b)

Figure (4) a) Input motions b) Fourier spectra of Input Motions.

2.4. Seismic Loading Test of Tunnel Model

The tamping method was used for soil preparation to get the required relative density. Two relative densities are used (30% for the first layer and 70%for the bottom layer). When the foundation level of the tunnel has reached, the soil surface has leveled and the tunnel placed at the middle of the container. Rod bolts (10mm) have been used to fix the tunnel ends. Then fix the pressure cell on the tunnel and accelerometers. After the tunnel installation has finished, the filling of soil has continued until reaching the final layer. Then the LVDT sensor is placed above the middle of the tunnel to record the settlement of the soil surface, see "Fig. 5".

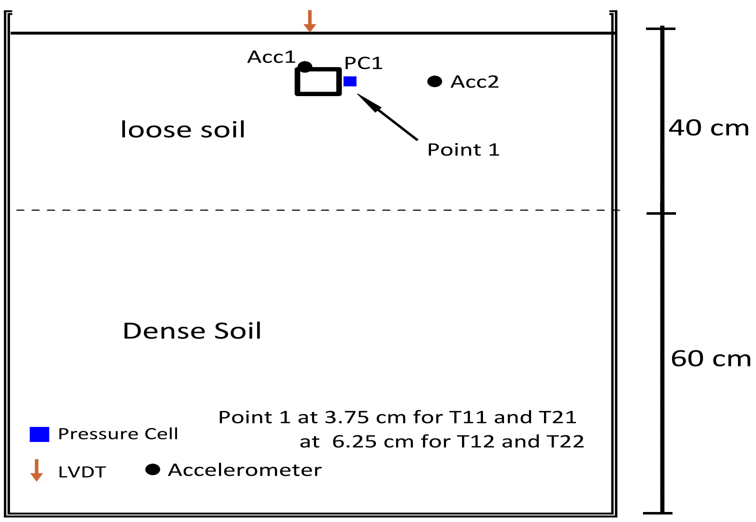


Figure (5) a) Sensors Distribution.

3. Results and Discussions

The model tests include studying the effect of the following parameters: i) soil saturation, ii) tunnel depth (H/W=1, 2) where H is the thickness of the soil layer above tunnel and W is tunnel width،. iii) input motion (0.05g, 0.1g, and 0.2g), and iv) direction of dynamic loading with respect to tunnel direction. The model tests divided into four groups (T11, T12, T21, and T22). Each group consist of 6 tests, see "Fig. 6".

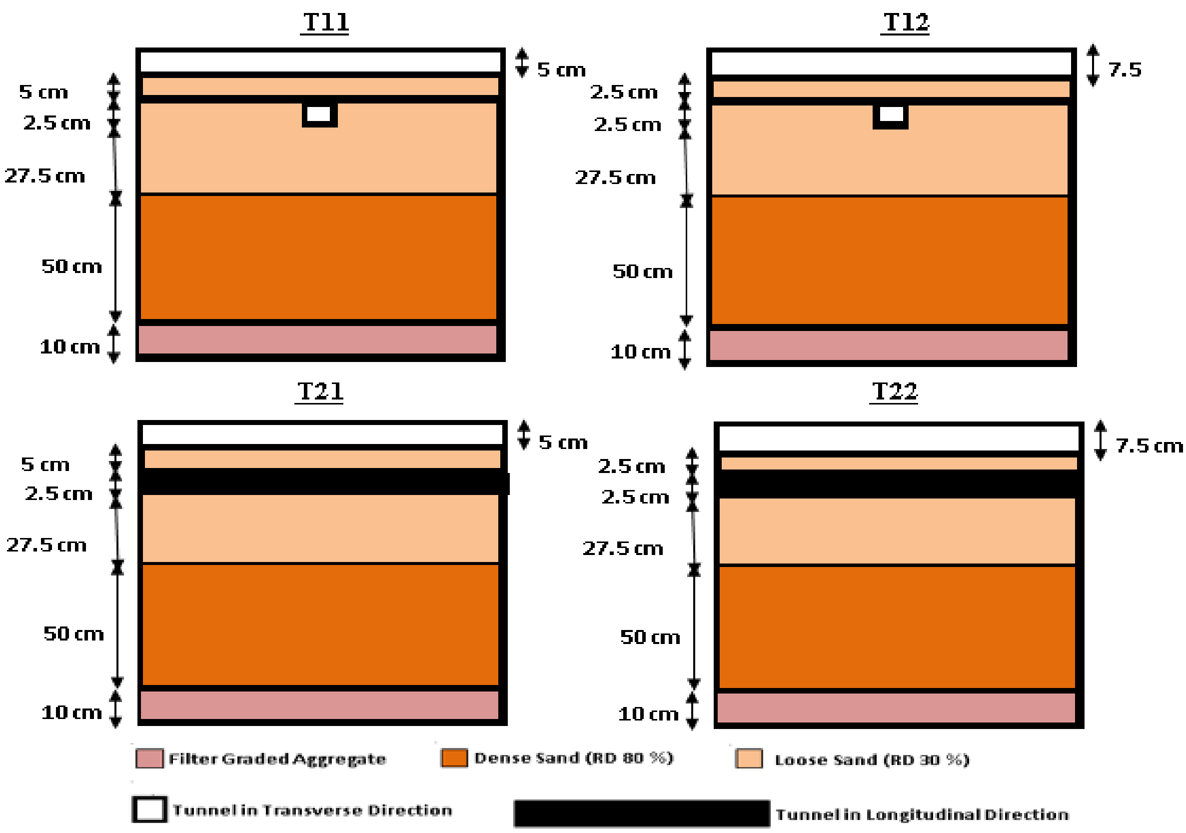


Figure (6) Group Definition.

3.1. Horizontal Acceleration

The horizontal acceleration recorded in two points on the tunnel and beside it see "Fig. 5". The effect of soil state (dry and saturated) on the horizontal acceleration has investigated for the three input motions in four groups T11, T12, T21, and T22. The change in the direction of ground acceleration has a significant effect on the horizontal acceleration especially in accelerometer1(Acc1) (on tunnel) and accelerometer2 (Acc2) (besides tunnel). It can be observed that the acceleration amplified towards the soil surface. This amplification is greater in the saturated soil than that in dry soil especially near the soil surface (accelerometer Acc2). The amplification increases with increases in ground acceleration. This is consistent with that has been deduced in previous studies such as [10], [9], and [14].

The horizontal acceleration of the tunnel model in T21 and T22 was less than that in T11 and T12. The horizontal acceleration besides tunnel, in some cases of T21 and T22 larger than that of T11 and T12 due to the interaction between the tunnel and the soil around it.

During the seismic loading, in the transverse direction on the tunnel section (T11 and T12), the movement of soil around the tunnel and the collision of waves of seismic loading with the tunnel is more than what's in the longitudinal direction for T21 and T22. The movement of the soil beside the tunnel during the shaking is more in the longitudinal direction and the collision among the soil, seismic wave, and the tunnel model lesser.

The effect of the H/W ratio on the horizontal acceleration of the tunnel and soil around it appears in dry and saturated soil. The horizontal acceleration in T12 and T22 is less than T11 and T21.

"Fig. 7"and "Fig. 8"show the effect of direction of seismic loading and H/W ratio on the horizontal acceleration of accelerometer Acc1 and Acc2 in dry and saturated soil for T11, T21, T12, and T22 respectively.

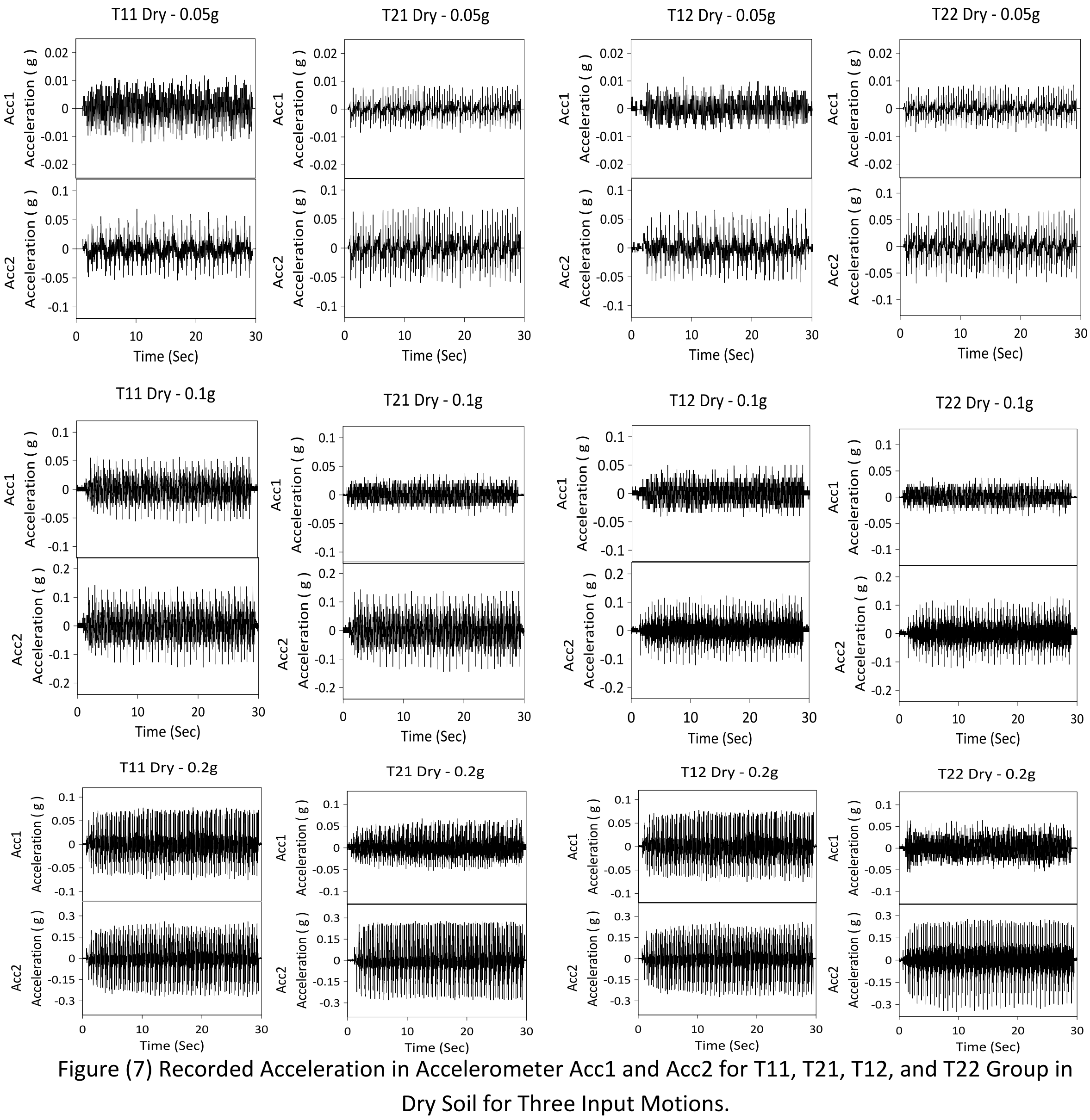


Figure (7) Recorded Acceleration in Accelerometer Acc1 and Acc2 for T11, T21, T12, and T22 Group in Dry Soil for Three Input Motions.

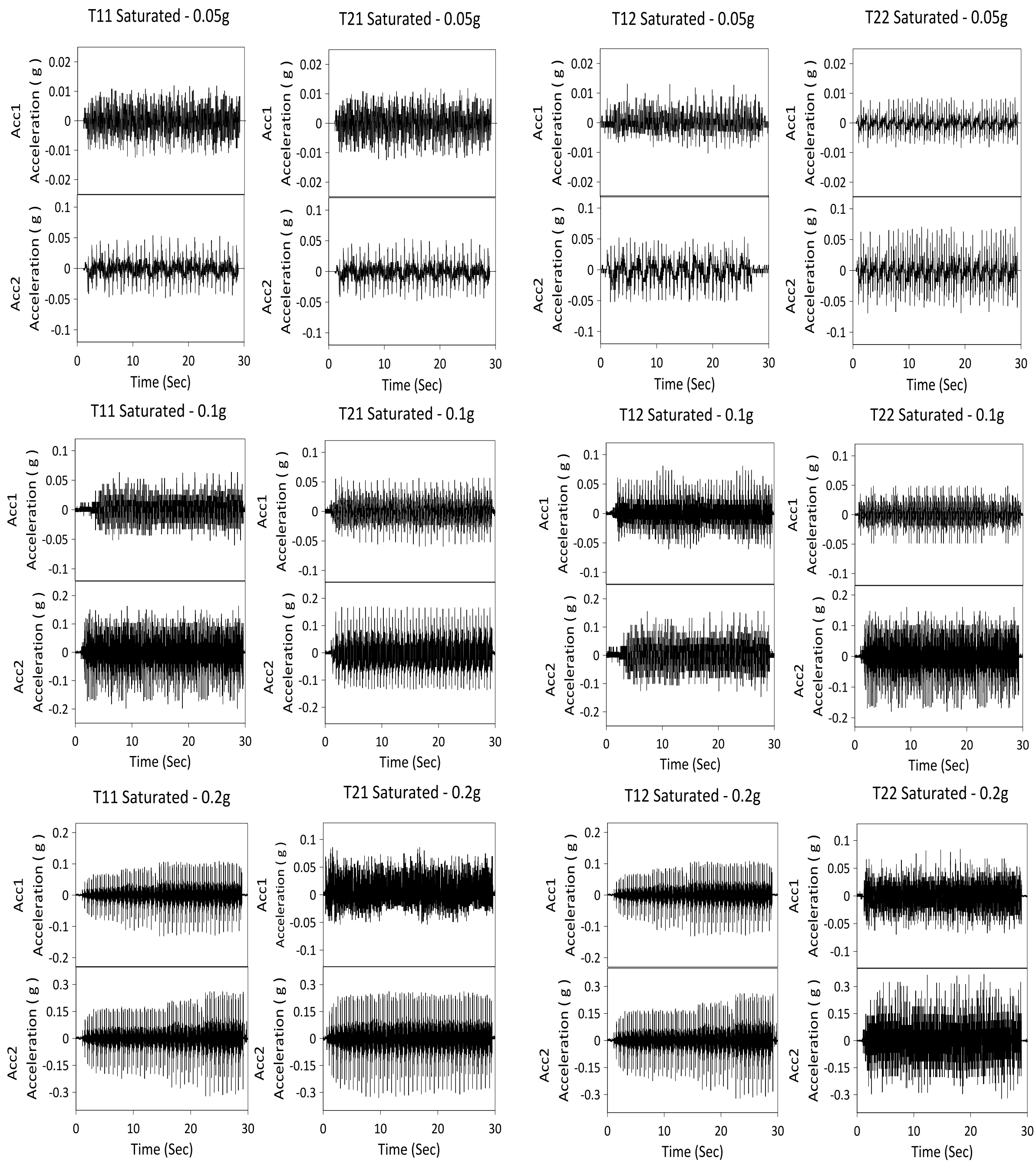
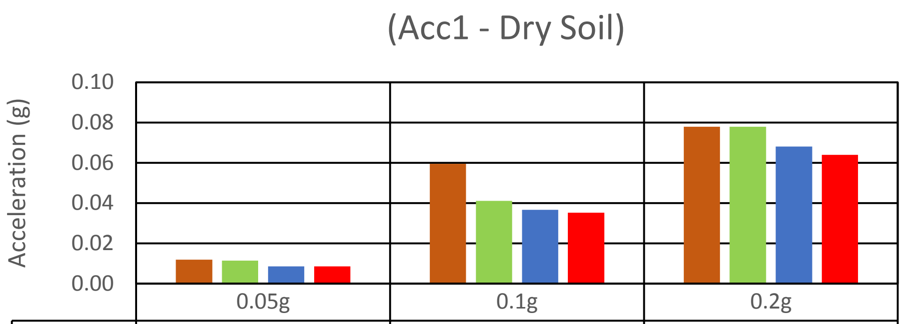


Figure (8) Recorded Acceleration in Accelerometer Acc1 and Acc2 for T11, T21, T12, and T22 Group in Saturated Soil for Three Input Motions.

"Fig. 9" presents the comparison between four groups (T11, T12, T21, and T22) for Accelerometer Acc1 in dry soil. In the seismic loading 0.05g, the maximum horizontal acceleration on the tunnel is (0.012g) for TL12, while, the minimum value is (0.0086g) in T21 and T22 respectively.

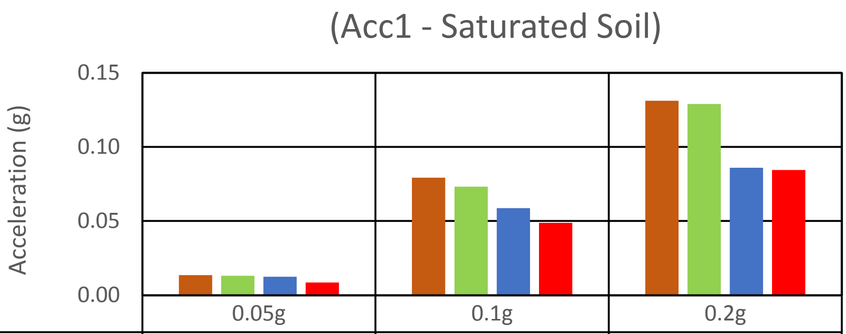
For seismic loadings 0.1g and 0.2g, the horizontal acceleration on the tunnel for T21 reduced by 38% and 15 %, if compared with T11, respectively. While the horizontal acceleration on the tunnel for T22 decreases by 15% and 22% if compared with T12.



	0.05g	0.1g	0.2g
T11 (Dry)	0.0120	0.0595	0.0780
T12 (Dry)	0.0115	0.0412	0.0780
T21 (Dry)	0.0086	0.0367	0.0681
T22 (Dry)	0.0086	0.0352	0.0639

Figure (9) Maximum Horizontal Acceleration of the Tunnel Model for T11, T12, T21, and T22 Group in Dry Soil for Three Input Motions.

"Fig. 10" illustrates the maximum horizontal acceleration of the tunnel model in four groups for saturated soil.

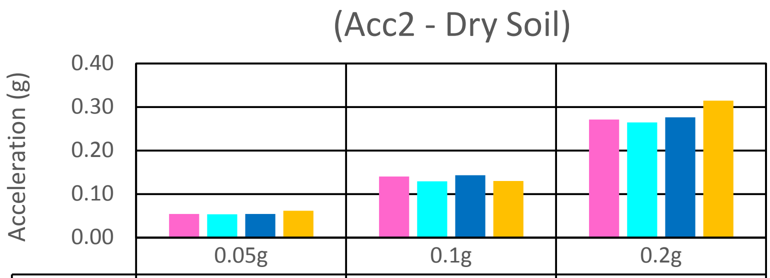


	0.05g	0.1g	0.2g
T11 (Saturated)	0.0135	0.0792	0.1312
T12 (Saturated)	0.0131	0.0732	0.1290
T21 (Saturated)	0.0125	0.0588	0.0860
T22 (Saturated)	0.0086	0.0489	0.0846

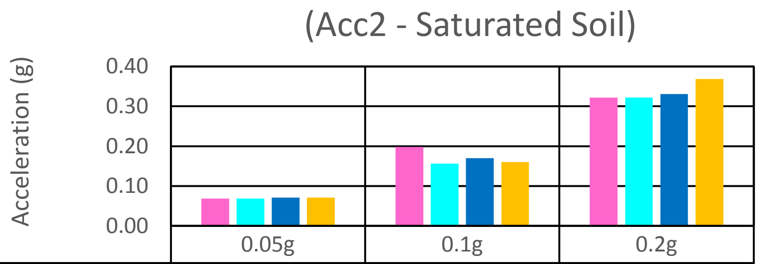
Figure (10) Maximum Horizontal Acceleration of the Tunnel Model for T11, T12, T21, and T22 Group in Saturated Soil for Three Input Motions.

"Fig. 11" shows the comparison of the maximum acceleration besides the tunnel model (Acc2) in four groups for dry and saturated soil. Generally, the horizontal acceleration for T21 and T22 increases if compared with T11 and T12 in the three seismic loading 0.05g, 0.1g, and 0.2g respectively. In the seismic loading 0.05g, the maximum acceleration is (0.0613g) for T22 in dry soil, while, in saturated soil, the maximum acceleration is (0.0708g) for T21 and T22. Also, in the seismic loading 0.1g, the maximum acceleration is (0.1431g) for T22 in dry soil, while, in saturated soil, the maximum acceleration is (0.1983g) for T11.

Finally, in the higher seismic loading 0.2g, the maximum acceleration recorded in T22. It is (0.301g) in dry soil, while, it has increased to (0.3689g) in saturated soil.



	0.05g	0.1g	0.2g
T11 (Dry)	0.0539	0.1400	0.2710
T12 (Dry)	0.0532	0.1295	0.2650
T21 (Dry)	0.0539	0.1431	0.2764
T22 (Dry)	0.0613	0.1301	0.3150



	0.05g	0.1g	0.2g
T11 (Saturated)	0.0687	0.1983	0.3217
T12 (Saturated)	0.0684	0.1562	0.3217
T21 (Saturated)	0.0708	0.1701	0.3307
T22 (Saturated)	0.0708	0.1603	0.3689

Figure (11). Maximum Horizontal Acceleration beside Tunnel Model (Acc2) for T11, T12, T21, and T22 Group in Dry and Saturated Soil for Three Input Motions.

3.2. Horizontal earth pressures on the tunnel side-wall

The dynamic earth pressure (DEP) has been measured on the right wall of the tunnel structure in all cases. In dry cases, generally, the DEP on the wall of the tunnel structure increases with increases of ground acceleration. This increment in DEP may be due to the densification of loose soil and yielding phenomena around the tunnel during shaking. During the ground acceleration 0.05g, the DEP in all groups is very low. The effect of depth of the tunnel on the response of DEP is clear. The DEP for T12 and T22 is greater than T11 and T21, while, the effect of the direction of ground acceleration on DEP is little, see "Fig. 12a".

For ground acceleration 0.1g and 0.2g, it is clear that the DEP increase with increasing the magnitude of seismic loading. In 0.1g, when increasing the depth of tunnel the DEP increases, hence when H/W equals 2 the DEP in T12 and T22 greater than T11 and T21.

The effect of ground acceleration direction can clearly be shown between T12 and T22 more than that between T11 and T21. The effect of ground acceleration can be attributed to the transmission of seismic wave loading from soil to tunnel structure, in T11 and T12 the wave of loading is perpendicular on the tunnel section that is lead to increase the DEP, while, in T21 and T22 the wave of loading is parallel to the wall of tunnel structure. In T11 and T12, the presence of tunnel structure in this direction causing non-uniform distribution of wave loading in soil; therefore, the intensity of wave loading is large on the tunnel section, while, in T21 and T22 the wave loading distributed uniformly in the soil because it is parallel to the wall of the tunnel structure. This may cause a decrease in DEP. Besides, the stresses that result from the transverse shear wave on the wall of the tunnel in T11 and T12 greater than that result from the longitudinal shear wave on the wall of the tunnel in T21 and T22.

The ground acceleration 0.2g is considerably very large if compared with 0.05g and 0.1g. The response of DEP in all groups is similar because of more densification of loose soil around the tunnel, therefore, the DEP increased. The DEP in T12 and T22 is greater than T11 and T21 respectively. The effect of direction of ground acceleration on DEP is low, see "Fig. 12b"and "Fig. 12c". This response of the DEP in dry soil approximately like that findings by [13].

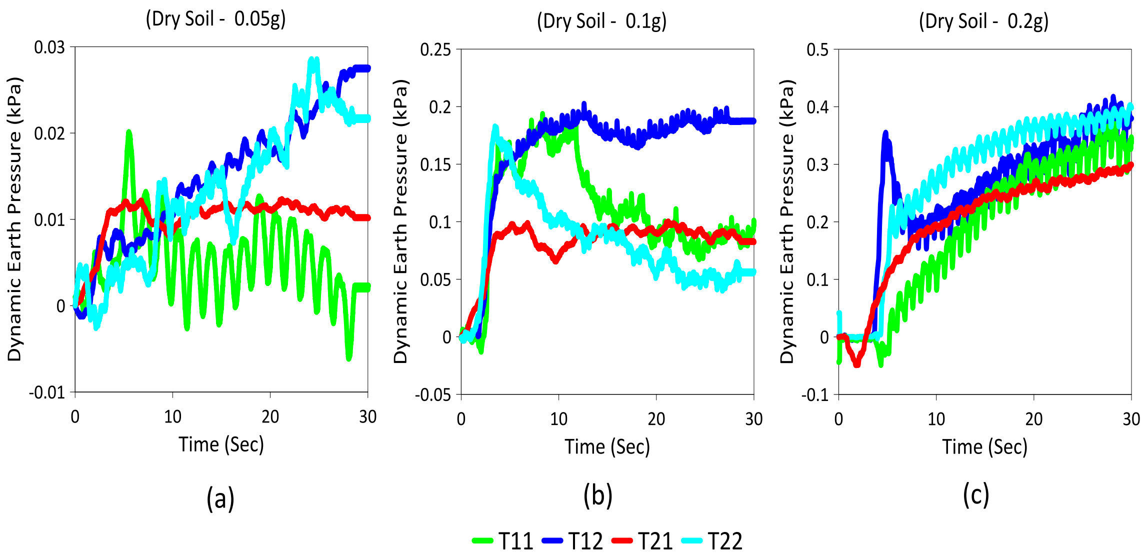


Figure (12) Dynamic Earth Pressure for Dry Cases.

The behavior of saturated soil around the tunnel is quite different from dry soil. The effect of pore water pressure highly appears in this case. In all saturated cases, the DEP is negative, while, it’s positive in dry cases. The negative DEP increases with increases in ground acceleration because the pore water pressure increased when ground acceleration increased. The negative DEP increases as the ground acceleration increases due to pore water pressure buildup. The buildup in pore water pressure leads to reduce the total thrust on the wall of the tunnel and cause liquefaction of soil around the tunnel (especially in seismic loading 0.2g). Besides, in saturated soil, the slip of soil around the tunnel is more than that in dry soil. In "Fig. 13", it can see the increment of negative DEP with the increase in seismic loading. Also, it can observe the effect of the depth of tunnel structure in all cases because the DEP in T12 is greater than T11 and DEP in T22 is greater than T21, while, the effect of direction of ground acceleration on the DEP in all cases is quite little for the three input motions.

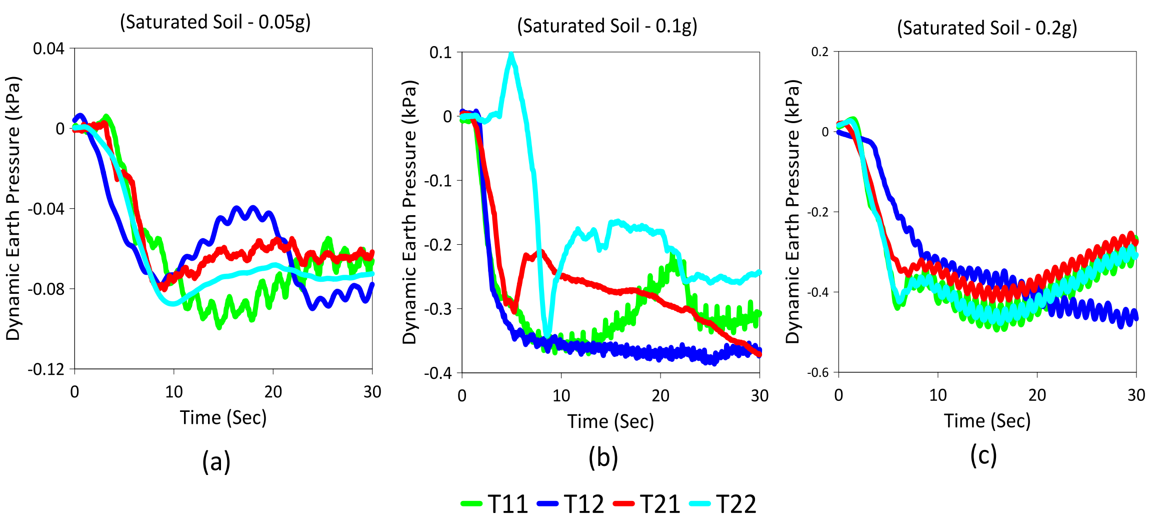


Figure (13) Dynamic Earth Pressure for Saturated Cases.

"Fig. 14" shows a comparison between the peak value of DEP for all groups in dry and saturated soil. For dry soil, the maximum DEP observed in T12 that's reached to (+0.027 kPa), (+0.2 kPa), and (+0.417 kPa) for the seismic loading 0.05g, 0.1g, and 0.2g respectively. Also, in saturated soil, the maximum DEP observed in T12. It was equal to (-0.099 kPa), (-0.38 kPa), and (-0.51 kPa) for the seismic loading 0.05g, 0.1g, and 0.2g respectively.

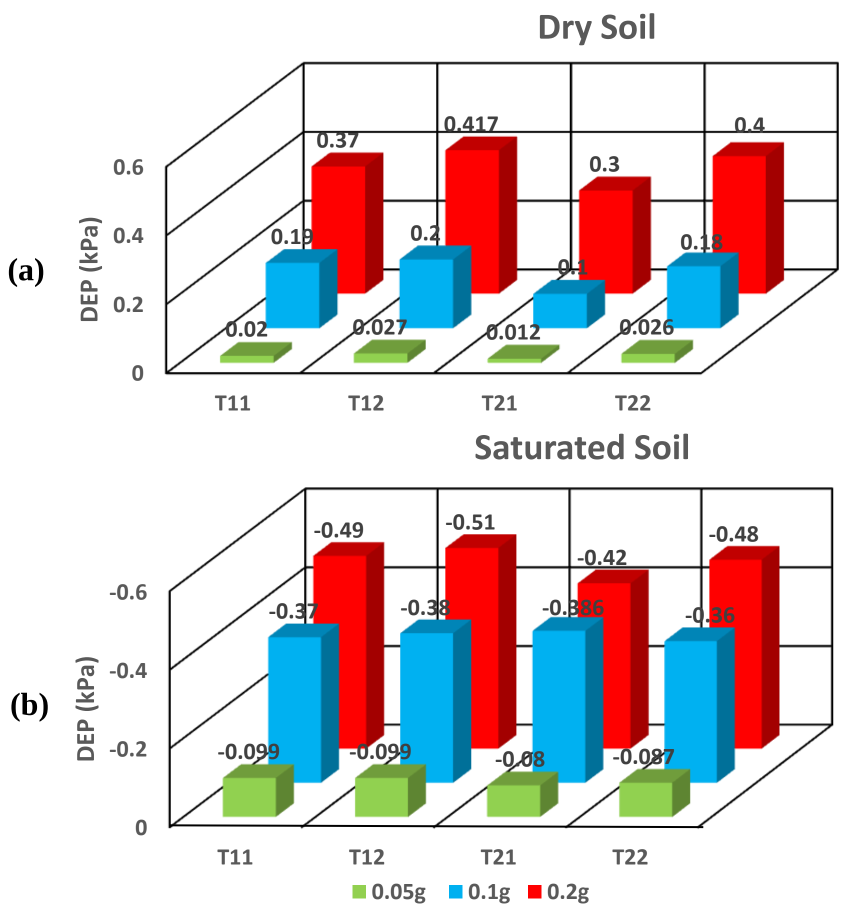


Figure (14) a) Peak of Dynamic Earth Pressure for Dry Cases b) Peak of Dynamic Earth Pressure for Saturated Cases

3.3. Soil Surface Settlement

The settlements of the ground surface have recorded above the center of the tunnel model using LVDT. In dry cases, the soil surface settlement in all groups increases as the ground acceleration increases due to more densification of loose sandy soil and the full slip of soil around the tunnel. The seismic load 0.05g has little effect on the settlement of the soil surface. The settlement of soil is quite similar in all groups. In other words, the effect of tunnel model depth and direction of ground acceleration is seemed low. Also, the effect of direction on the soil surface settlement is small for ground acceleration 0.1g and 0.2g. While the effect of tunnel model depth in 0.1g is noticeable where the settlement of T12 and T22 is less than T11 and T21 respectively. It is observed a contrary behavior at ground acceleration 0.2g where the settlement of T11 and T21 is less than T12 and T22 respectively. This behavior can be attributed to the thickness of the loose soil layer above the tunnel structure in T12 and T22 is greater than its thickness in T11 and T21 due to the large slip of soil around the tunnel because of the highly seismic load see "Fig. 15". This results associate the findings by [1].

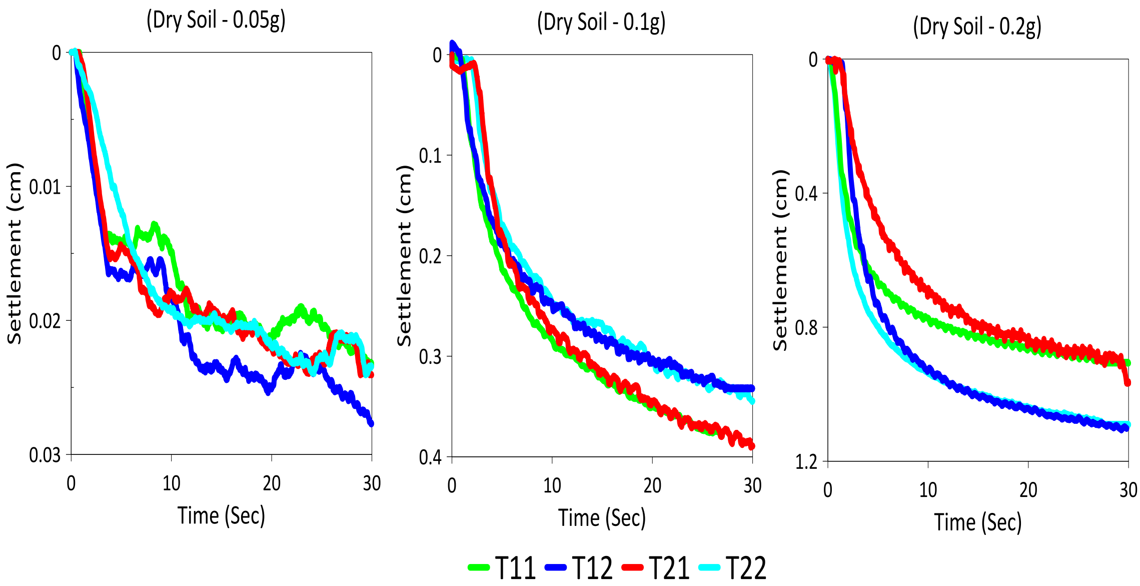


Figure (15) Final Soil Surface Settlement for Dry Cases.

For saturated soil, the settlement increases with the increase of ground acceleration when compared with the dry soil test results due to the increases in pore water pressure. The increase of ground acceleration leads to reduce the shear strength of soil, especially for input motion 0.1g and 0.2g. Because the increase of pore water pressure in voids between particles lead to increase the spacing between these particles as result decrease the contact pressure between soil particles and the friction between soil and tunnel. In cases of ground acceleration 0.05g, the soil surface settlement in T11 and T12 is greater than the settlement T21 and T22 because the transverse direction of seismic loading on the tunnel section in T11 and T12 lead to decrease in shear strength of soil around tunnel more than the longitudinal direction in seismic loading in T21 and T22. The effect of tunnel model depth in this case of loading is quite little.

The effect of ground acceleration direction on the soil surface settlement is small for all groups in 0.1g. The increase in depth of the tunnel model leads to an increase in the settlement of the soil surface, while, in the cases of 0.2g ground acceleration (highly ground shaking) the settlement are largely increased if compared with 0.05g and 0.1g because the high buildup of pore water pressure leads to largely decrease in soil resistance and increasing the slip of soil around the tunnel. For ground acceleration 0.2g, the liquefaction occurs in all cases lead to an increase in the settlement. The settlement in T12 and T22 is greater than T11 and T21. This behavior may be due to the greater thickness of the loose soil layer, see "Fig. 16".

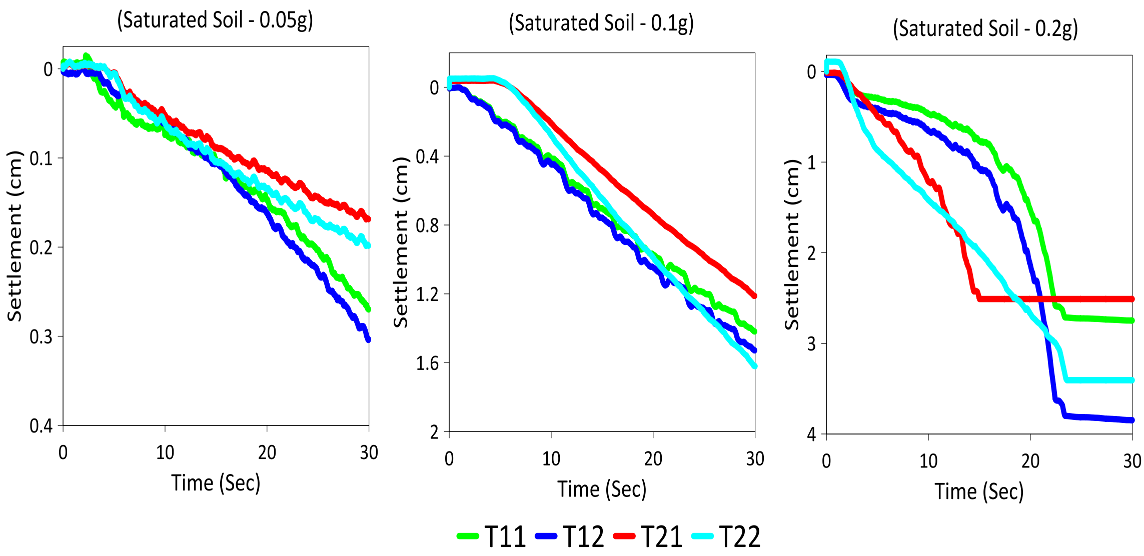


Figure (16) Final Soil Surface Settlement for Saturated Cases.

"Fig. 17" and "Fig. 18" presents the comparison between the final soil surface settlement in dry and saturated soil for all cases. For cases of dry soil, the settlement at the end of seismic loading 0.2g is about (39 to 47) times that of 0.05g, while, it is about (2.4 to 3.2) times that of 0.1g. In saturated soil, the settlement for seismic loading 0.2g is about (8.3 to 23.6) times that of 0.05g, while, it is about (2.05 to 2.51) times of 0.1g

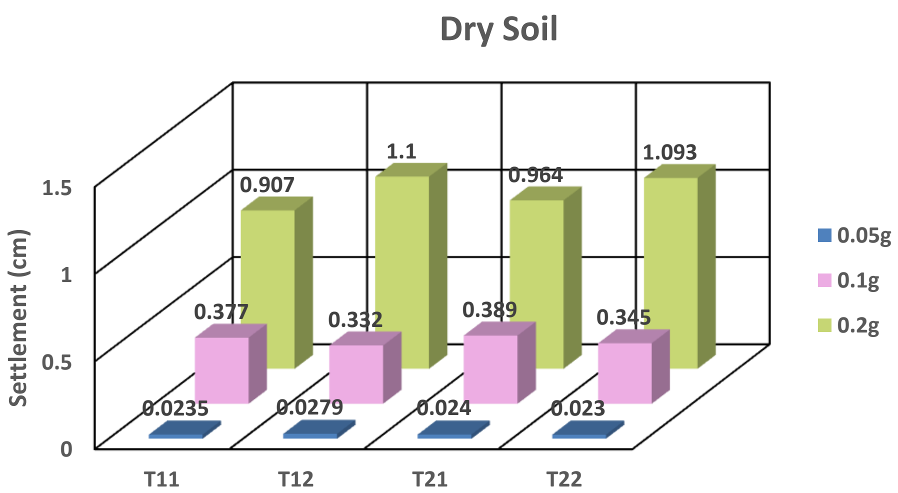


Figure (17) Final Soil Surface Settlement for Dry Cases.

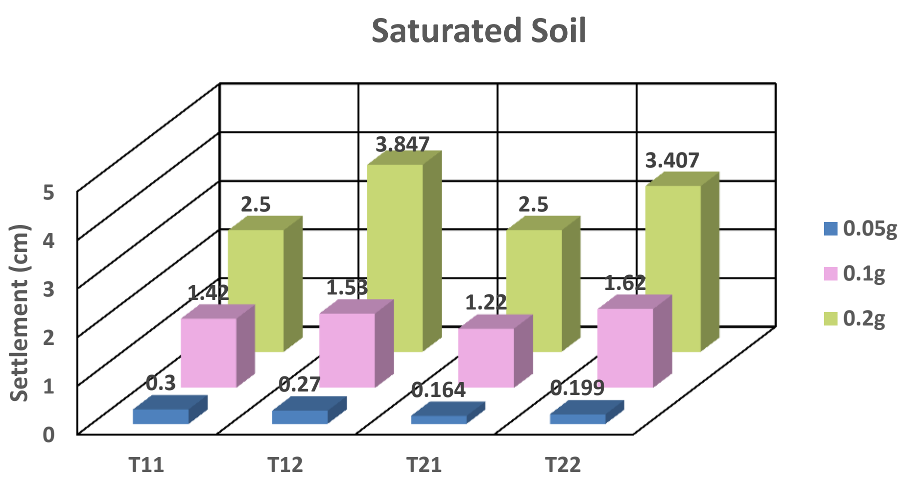


Figure (18) Final Soil Surface Settlement for Saturated Cases.

4. Conclusions

1. The acceleration amplified towards the soil surface. This amplification is greater in the saturated soil than dry soil especially near the soil surface.
2. The horizontal acceleration of the tunnel model in T21 and T22 was less than that in T11 and T12. While, the horizontal acceleration besides tunnel, in some cases of T21 and T22 larger than that of T11 and T12 due to the interaction between the tunnel and the soil around it.
3. The increase of the H/W ratio lead to decrease the horizontal acceleration of the tunnel and soil around it appears in dry and saturated soil. The horizontal acceleration of the tunnel model in T12 and T22 was less than that in T11 and T21.
4. In dry cases, the increment in positive DEP is due to the densification of loose soil and yielding phenomena around the tunnel during shaking, while in saturated cases, the negative DEP, due to increment in pore water pressure, leads to reduce the total thrust on wall of tunnel and causing liquefaction of soil around the tunnel especially in seismic loading 0.2g.
5. The effect of direction of ground acceleration and tunnel model depth on DEP are tangible in dry cases for 0.05g and 0.1g, while, this factor has little effect in 0.2g. In saturated cases, the effect of tunnel model depth on the results of DEP is greater than the effect of direction of ground acceleration.
6. In dry cases, the soil surface settlement increases with an increase in ground acceleration in all groups due to more densification of loose sandy soil around the tunnel. The full slip of soil around the tunnel leads to increase settlement of soil. The effect of depth of tunnel model and direction of ground acceleration for 0.05g is quiet little, while, for ground acceleration 0.1g and 0.2g the effect of direction on the soil surface settlement is small. The effect of tunnel model depth is noticeable.
7. For saturated cases, the soil settlement increases with increase in ground acceleration due to the increases of pore water pressure with increases of ground acceleration that is lead to reduce the shear strength of soil, especially for input motion 0.1g and 0.2g. The effect of tunnel model depth and direction of ground acceleration for 0.05g and 0.1g seemed clear.

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