Assessment of Soil Tunnel Interaction in Sand Soil

Omar Yaseen Almashadany1, * and Bushra Suhale Albusoda 1

1 College of Engineering, University of Baghdad, Baghdad, Iraq.
*Corresponding author, email: omar.yasin66@yahoo.com

Abstract. In this study, series of shaking table tests were carried out to investigate the effect of tunnel model depth and direction of ground acceleration on the ground surface settlement and the dynamic earth pressure on the tunnel wall. Box tunnel model is embedded in dry and saturated soil (Karbala Sand). It subjected to three input sinusoidal motions 0.05g, 0.1g, and 0.2g. Two relative densities were used, 30% for the upper layer and 70% for the lower layer. The results obtained indicate that the settlement of soil surface increases with an increase in ground acceleration. The increase in tunnel model depth leads to an increase in settlement especially at 0.2g earthquake loading (for saturated and dry soil). 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.

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 been 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, 10], and experimental studies [11, 13]. 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 tunnel response at different depths and the horizontal earth pressure on the tunnel side walls.

2. Experimental Programs
2.1. Physical properties of soil
In the present study, Karbala sand has been used. Standard tests were carried out according to ASTM standards to determine the physical and mechanical properties of sand. Figure 1 shows the grain size distribution of the soil [4], while the physical properties of sandy soil have been presented in table 1.
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 figure 2.

![Figure 1. Grain size distribution for sand.](image1)

![Figure 2. Tunnel model.](image2)
The mechanical properties of the tunnel model have determined by the tensile test according to ASTM specification [7]. 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 $\nu$ | Modulus of Elasticity $E$ (N/mm$^2$) |
|--------------------|-----------------------------|------------------------|--------------------------------------|
| Value              | 1953.13                     | 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: 1) Shaking table base and Electrical motor, 2) Steel box; and 3) Damping system, see figure 3.

**Figure 3.** Shaking table: 1) Shaking table base and electrical motor 2) Steel box; and 3) Damping system.

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 figure 4.
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. 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 figures 5.

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 consists of 6 tests, see figures 6 and figure 7.
3.1. 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. This results associate the findings by [1].

For saturated soil, the settlement is greater with the increase in ground acceleration if 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.

Figure 8 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.

![Dry](image1)

![Saturated](image2)

**Figure 8.** Final soil surface settlement for dry and saturated cases.
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 figure 9a.

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 figure 9b and figure 9c. This response of the DEP in dry soil approximately like that findings by [12].

![Figure 9. Dynamic earth pressure for dry cases.](image)

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 Figure 10, 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 10. Dynamic earth pressure for saturated cases.

Figure 11 and figure 12 show 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 11. Peak of dynamic earth pressure for dry cases.
4. Conclusions
1. In dry cases, the soil surface settlement increases with an increase in ground acceleration in all groups. The increase in the settlement is 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.
2. 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. For ground acceleration 0.2g, because of occurrences of liquefaction, these factors have a small effect.
3. 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. Further, in saturated soil, the soil slip around the tunnel is more than that in dry soil.
4. 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.

References
[1] Abuhajar O El Naggar H and Newson T 2015 Seismic soil-culvert interaction Can. Geotech J (52) 1–19
[2] Al-Recaby M K, Fattah M Y and Karim H H 2016 Dynamic Behavior of Pile Group Model in Two-Layer Sandy Soil Subjected to Lateral Earthquake Excitation Global Journal of Engineering Science and Research Management vol 3 no 8 pp 57-80
[3] ASTM D3080-1998 Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions American Society for Testing and Materials
[4] ASTM D422-2001 Standard Test Method for Particle Size-Analysis of Soils American Society for Testing and Materials
[5] ASTM D4253-2000 Standard Test Method for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table American Society for Testing and Materials
[6] ASTM D4254-2000 Standard Test Method for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density American Society for Testing and Materials
[7] ASTM D638-2003 Test Method for Tensile Properties of Plastics American Society for Testing and Materials
[8] ASTM D854-2005 Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer American Society for Testing and Materials
[9] Baziar M H Moghadam M R Kim D S and Choo Y W 2014 Effect of underground tunnel on the ground surface acceleration Tunnelling and Underground Space Technology (44) 10–22
[10] Lanzano G Bilotta E Russo G and Silvestri F 2015 Experimental and numerical study on circular tunnels under seismic loading European Journal of Environmental and Civil Engineering, 19(5) 539-563
[11] Tsinidis G Heron C Pitolakis K and Madabhushi S P G 2015b Centrifuge modelling of the dynamic behavior of square tunnels in sand In Taucer F. and Apostolska R. (eds.) Experimental research in earthquake engineering - EU-SERIES concluding workshop, Geotechnical Geological and Earthquake Engineering, (35) 509-523, Springer International Publishing, Switzerland
[12] Tsinidis G Rovithis E Pitolakis K and Chazelas J L 2016b Seismic response of boxtype tunnels in soft soil: experimental and numerical investigation Tunn.Undergr. Space Technol. (59) 199–214
[13] Yu Haitao Yuan Yong Li Chong Yan Xiao and Yuan Juyun 2016 Multi-point shaking table test for long tunnels subjected to non-uniform seismic loadings – Part I Theory and validation Soil Dynamics and Earthquake Engineering. (108) 10.1016/j.soil dyn.