https://doi.org/10.33261/jaaru. 2022.29.3.004 *Association of Arab Universities Journal of Engineering Sciences (2022)29(3): 29–35*

Association of Arab Universities
Journal of Engineering Sciences
مجلة اتحاد الجامعات العربية للدراسات والبحوث الهندسية

كلية الهندسة - جامعة بغداد

جمعية كليات الهندسة
اعضاء اتحاد الجامعات العربية

A Numerical Study on the Behavior of NATM Tunnels under Seismic Loading

***Hayder A. Al-Mirza*[1,*], and *Mahdi O. Karkush*[2]**

[1] *Department of Civil Engineering, University of Baghdad, Baghdad, Iraq, h.almirza1901m@coeng.uobaghdad.edu.iq*

[2] *Department of Civil Engineering, University of Baghdad, Baghdad, Iraq, mahdi_karkush@coeng.uobaghdad.edu.iq*

**Corresponding author: Hayder A. Al-Mirza, email: h.almirza1901m@coeng.uobaghdad.edu.iq*

Abstract— The necessity of tunnels is becoming more and more essential in the modern world because of their various purposes and independence of the surface life despite their shape. This paper aims at examining the behavior of a seismically loaded New Austrian Tunneling Method (NATM) tunnel buried in well graded gravel. The maximum displacement due to overburden pressure was obtained which was 30.38 mm as well as the vertical and lateral displacements of a maximum 53 mm and 17 mm, respectively. The peak ground acceleration (PGA) is found to be normal when comparing it with the PGA map of Iraq. Lastly, the Fourier amplitude spectrum was represented in order to show its relationship with the ground input energy.

Keywords— Tunnel, NATM tunnels, seismic loading, numerical analysis, soil.

1. Introduction

In today's world, especially in heavily populated urban areas, the need for making use of underground space is an essential aspect in order to preserve nature and surface life. One of the main components of the modern transportation network is the subway which despite its high cost compared to other alternatives, has a number of environmental, geological and economic advantages. According to Balasubramanian [1], tunnels are structures built underground used for transporting people and goods, water as well as sanitation. Because they extend to certain depths, they are considered environmentally friendly compared to other alternatives in addition to the fact that they do not affect traffic, flora nor fauna when constructed. There are static forces that engineers should be focusing on when designing a tunnel in order to achieve equilibrium between the structure and soil as well as the dynamic loads represented as seismic loads. Static forces include compression, tension, shearing and torsion.

On the other hand, Hassanlourad et al. [8] stated that the design and excavation of underground structures and the static and seismic loading exerted on them have become a challenging field for geotechnical engineers. The reason for that is because of the earthquakes that have occurred during the last decades such as Kobe in 1995 that left a number of tunnels extremely damaged. According to Tsinidis et al. [4], given the size and importance of the tunnel infrastructure whether as transportation or utility tunnels and the significant amount of money they cost, it is only reasonable to investigate the effect of earthquake loading on them because the direct or indirect losses they cause. This effect may fall into the different stages of constructing a tunnel such as design, analysis, construction or the risk assessment.

It was only in recent years and particularly in 1993 after several earthquakes caused deformations in tunnels that researchers have found a relationship that combines the interaction between ground and tunnel. Wang has emphasized the parameter of flexibility as an explanation of the deformed tunnel in relation to the surrounding ground under seismic loading. An example of tunnels not properly designed to resist the earthquake effect is Daikai Subway in Japan during the Hyogoken Nambu earthquake because the subway parts have experienced earthquake wave propagation each with different acceleration. Not to mention the case where the Longxi tunnel in China has collapsed in 2008 during the Wenchuan earthquake [4]. Along with other cases, these have been of important use as large-scale cases to assess the vulnerability and behavior of tunnels that could not be obtained in experimental or numerical analyses. NATM is a tunneling process that is used for certain geological conditions and gives the tunnel a specific shape. Due to the deformations tunnels suffer from during seismic loadings, the purpose of this research paper is to evaluate the behavior of NATM tunnels under seismic loadings along with overburden pressure and whether they can resist these loads without any excessive settlement or shape deformations. Numerical modeling using finite element analysis (FEA) was used to achieve the purpose of this study based on previous works.

2. Seismic Loading Condition

In order to better comprehend the forces contributing to the stresses in a tunnel, one should understand where these forces generate from. According to [3, 13], there are certain types of elastic waves resulting from an earthquake, two of them are called “body waves” that travel within the earth and include S-wave and P-wave. The second two types that travel along the surface of the earth are called “Rayleigh wave” and “Love wave”.

The pressure wave has other names like primary wave or compressional wave and is the wave that has the greatest velocity compared to others. It results from alternating compression and expansion of soil particles through which they propagate and these particles are parallel to the propagation of these waves. Also, it can travel though air taking the form of a sound wave at velocity approximately 330 m/s. The shear wave has other names also such as shaking waves or secondary waves which is a wave traveling at a slower velocity than the first one in a transverse direction. They travel in soil particles sliding past each other which means that the motion of soil particles is perpendicular to the wave propagation. The difference between this wave and the former is that it cannot travel through air or fluids but because of their large amplitude, they are considered more destructive.

The Rayleigh waves are named after (Lord Rayleigh) the British Physicist and they result from the interaction of the body waves and they can easily be observed in open spaces because they take the form of ocean waves. This R-wave was proven to be a combination of the dilation and compression in the longitudinal direction and forms an elliptical shape. The love wave was discovered by “A.E.H. Love” the British Seismologist and it travels in a perpendicular direction to the propagation and does not affect the longitudinal nor the vertical displacements. Its velocity is greater than that of the Rayleigh wave and can cause shearing in the ground in a horizontal direction.

Based on seminal work carried out by (Owen and Scholl, 1981) and (Sharma and Judd, 1991), Tsinidis et al. [4] have emphasized that deep underground tunnels or tunnels in rock layers have suffered slight or no damage for peak ground acceleration (PGA) less than 0.4g. Moreover, when decreasing the epicentral distance or increasing the earthquake magnitude they can suffer more damage. Using the aforementioned Hyogoken Nambu earthquake in china, for instance, Power et al. [11] have used this example as a basis for determining the relationship of PGA and tunnel deformation. While it is noteworthy to mention that this earthquake has caused heavy damage to 12% of tunnels within the epicentral area, they found that for tunnels minor damage happened for PGA less than 0.2g while it tends to be heavier when PGA is greater than 0.2g.

3. Stresses and Displacement of Tunnels

It is worth noting that according to observations of California earthquakes, it was generally found that the horizontal ground motion to be more severe than the vertical one keeping in mind that the shear wave propagating in the vertical direction represents the horizontal ground motion and vice versa. This effect is called the strike-slip fault while the thrust fault is generally caused by vertical ground motion equaling or exceeding the horizontal motion [6]. This motion along with the static loading of the ground can exert stresses on the tunnel in the vertical, lateral and longitudinal directions. Moreover, the vertically propagating shear wave will cause some changes in the shape of the tunnel whether it was circular, rectangular and so on. On the other hand, according to Gil et al. [7], the depth to which the tunnel is constructed governs the behavior of the soil and structure meaning that when the tunnel is shallow the soil and tunnel tend to behave as a whole body. In contrast, when the tunnel is deep it behaves somehow as a rigid body while the soil above the tunnel tends to vibrate by itself. In addition, the distance of influence from the axis of the tunnel is high and unrealistic in the first case while it has a great value in the second one.

According to Lu et al. [12], when a tunnel is subjected to a P-wave or S-wave at an angle Ø to the tunnel axis which is described in the previous section, its behavior in the longitudinal direction is somewhat similar to that of an elastic beam experiencing deformations by the ground surrounding it. On the other hand, axial and curvature deformations happen in horizontal tunnels (i.e. in most cases) when the seismic wave spreads along or indirectly to the tunnel where the tunnel acts somehow exactly like an elastic beam when subjected to imposed strains. When the seismic wave propagates in a parallel direction to the tunnel, this will produce compression or tension in an alternating sense. In order to take this into consideration, the tunnel design criteria should include this effect in the longitudinal direction. Furthermore, the ovaling and racking effect is observed when the seismic wave spreads normal or near-normal to the tunnel which results in changes in the shape of the tunnel in terms of its cross-section. Ovaling happens in circular tunnels while racking is observed in rectangular tunnels. These types of deformation, when designing the tunnel lining should be taken into account in the transverse direction. Previous studies have found that there are vertical, horizontal and indirect effect of wave propagation and the vertical shear wave is the one that governs the tunnel behavior against these two deformations.

4. Numerical Modeling

This approach is the process of representing a physical behavior in mathematical equations and is widely used in structural and geotechnical engineering [2]. This method creates a numerical model that will then be compared to experimental tests in order to validate it. The advantage of this method is that when there is good correspondence with experiments, the process of validation and parametric study will become easy. Another advantage is that it takes less time and cost compared to traditional trial and error processes. The only shortcoming of this method is the difficulty in creating a model in a realistic case as well as assessing the obtained results. In general, this approach plays a significant role in providing sophisticated design and development regarding material handling. Numerical modeling includes finite element, discrete element, boundary element and finite difference methods. Any method can be used to express the physical case in the form of a mathematical representation in order to describe the behavior of a soil or a structure under certain conditions. The main criterion that should be followed here is to use the model to get an idea of the soil-structure interaction. This is due to that fact that an underground structure behaves according to the soil surrounding it and depends on its characteristics. In this paper, PLAXIS 3D will be used to create an FE model of an NATM tunnel buried in a rock-type soil under overburden and seismic loadings (see **Figure 1**).

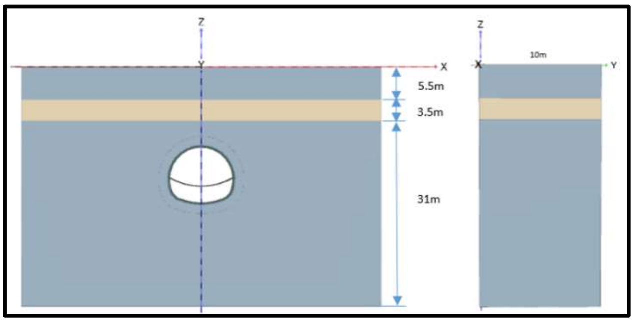

Figure 1: PLAXIS 3D model of NATM tunnel.

According to Fasihnikoutalab et al. [10], the soil used in the model consisted of three layers, the first and third layers were well-graded gravel (GW) while the second layer was silty gravel (GM). The thickness is illustrated in **Figure 1** and the characteristics for the soil and tunnel lining were also specified as shown in **Tables 1** and **2**.

Table 1: Soil characteristics.

Parameter	**GW**	**GM**	**Unit**
Material model	Mohr-Coulomb	Mohr-Coulomb	-
Material behavior	Drained	Drained	-
Unsaturated unit weight	19.81	19.52	kN/m3
Saturated unit weight	21.13	20.94	kN/m3
Stiffness	98×10^3	68.67×10^3	kPa
Poisson's ratio	0.3	0.3	-
Cohesion	49	12.75	kPa
Internal friction	45	40	o

Table 2: Tunnel lining characteristics.

Parameter	TBM	Unit
Material type	Elastic	-
Thickness	0.25	m
Unit weight	33	kN/m3
Stiffness	32×10^6	kPa
Poisson's ratio	0.15	-
Shear modulus	13.91×10^6	kPa

After specifying the properties for each element, the next step was creating the tunnel at 23m depth and the tunnel shape was created according to NATM excavation method in the tunnel designer tool. After creating the segments and subsections and given the properties as shown in Table 2, the next thing was to give a trajectory of 20m in length with 2m for each slice. After that the sequencing of the tunnel was given four steps, two for excavating the crown and invert and two for applying the tunnel lining and interface between soil and tunnel (see **Figure 2**).

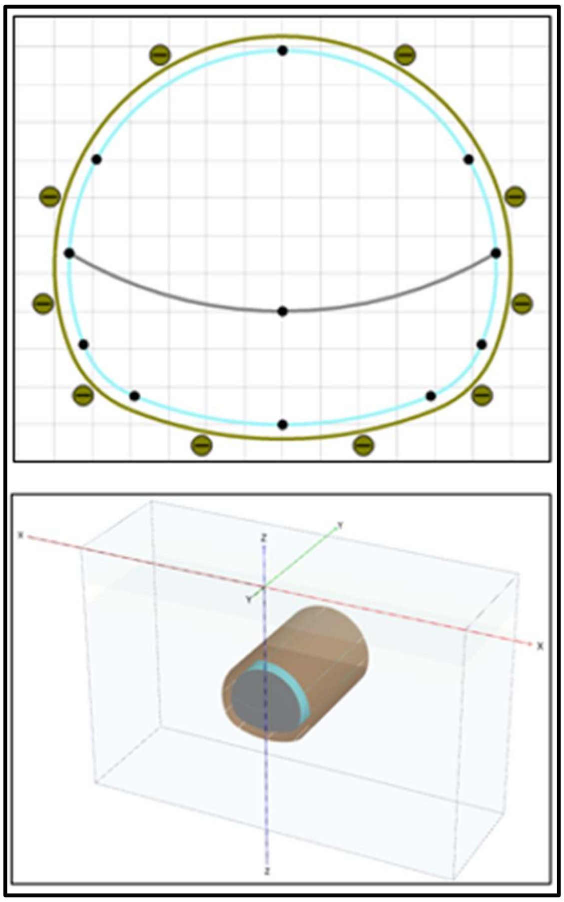

Figure 2: Tunnel cross section and interface.

Figure 3 explains how the tunnel is being excavated and the lining is being applied for both the crown and invert of the tunnel. It is worth mentioning that the interation for each 4 successive steps was done using Python.

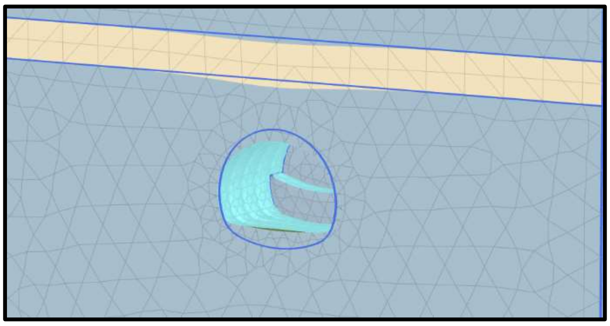

Figure 3: NATM excavation process.

The stages for construction were 40 with each stage being iterated for different number of times and after that the seismic loading was applied for frequency equal to 5 Hz [9]. The dynamic time was set at 0.5 s, the Paradiso multicore direct solver type was used and the tolerated error was 0.01. Phases 41 and 42 were about applying vertical and lateral seismic loadings to the tunnel where we reset the displacements for these phases to obtain separate results.

5. Results and Discussion

The tunneling process was carried out according to the tunnel designer tool and classified into excavation and lining installment. Phase 1 was about excavating the tunnel crown, Phase 2 was installing the tunnel lining for the top part, Phase 3 included excavating the invert and Phase 4 was installing the lining for the bottom part. The first slice was created by these 4 phases, each slice was 2 m in length and the whole tunnel consisted of 10 slices. **Figure 4** shows the maximum vertical settlement due to the overburden pressure which was 30.38 mm and the maximum lateral displacement was 7.17 mm.

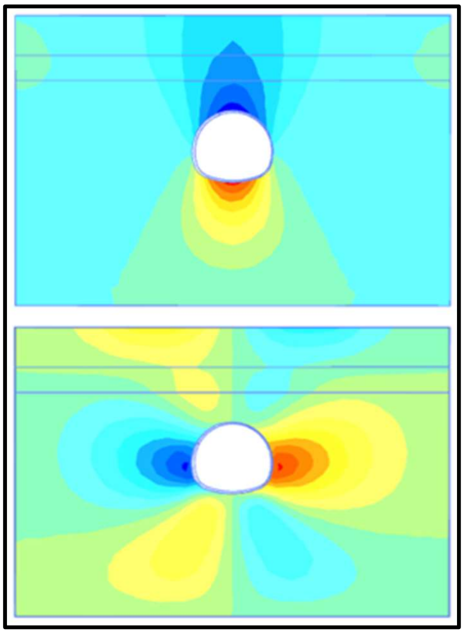

Figure 4: Vertical and lateral displacement illustrations.

When the aforementioned seismic loading was applied in the vertical direction in Phase 41, **Figure 5** was obtained showing the vertical displacement at the crown and invert at the portal, 5m and 10m of the tunnel lining, respectively.

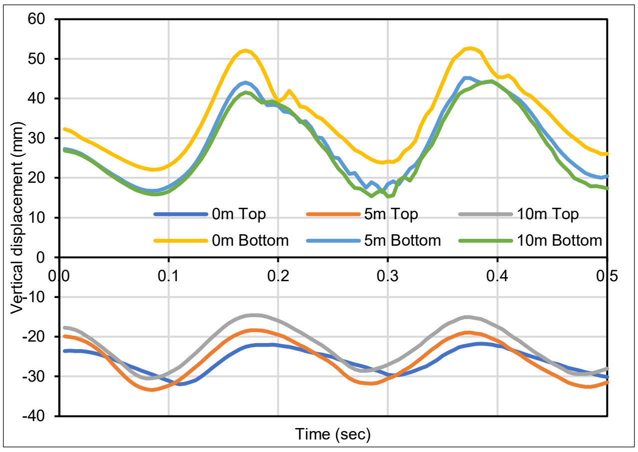

Figure 5: Vertical displacement for top and bottom nodes.

It can be found that the maximum value of displacement at the top was 33mm downward at 5m length and the maximum value at the bottom was 53 mm upward at the portal. On the other hand, the seismic loading was applied in the lateral direction during Phase 42 which was independent of the previous phase so as to take each one at a time. The following figures illustrate the lateral displacements at the same locations as the previous figures.

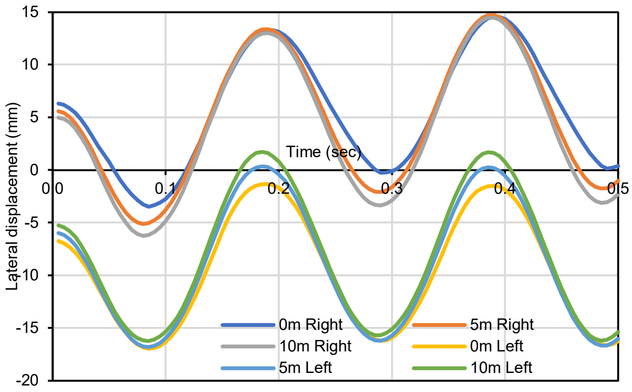

Figure 6: Lateral displacement for right and left nodes.

The maximum values of lateral displacement was 15 mm at the right side 5 m from the tunnel face while it was 17 mm at the left side at the portal (see **Figure 6**). In addition, the peak ground acceleration (PGA) due to lateral seismic loading was also obtained. One can notice that the PGA value is 1.07 at a point chosen on the soil surface when the tunnel is subjected to lateral seismic loading (see **Figure 7**). As shown in **Figure 8** which illustrates the PGA map of Iraq, when this value is compared to the values from the map, it can be considered reasonable because it is close to the maximum value shown in the map [5].

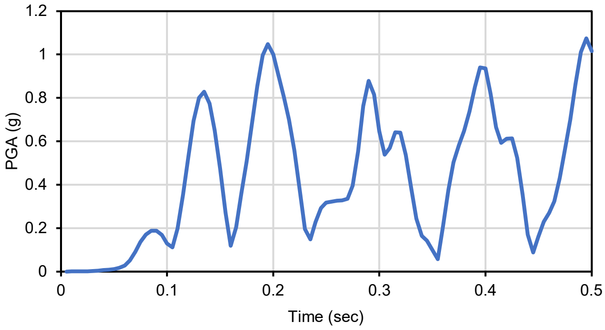

Figure 7: Peak ground acceleration versus dynamic time.

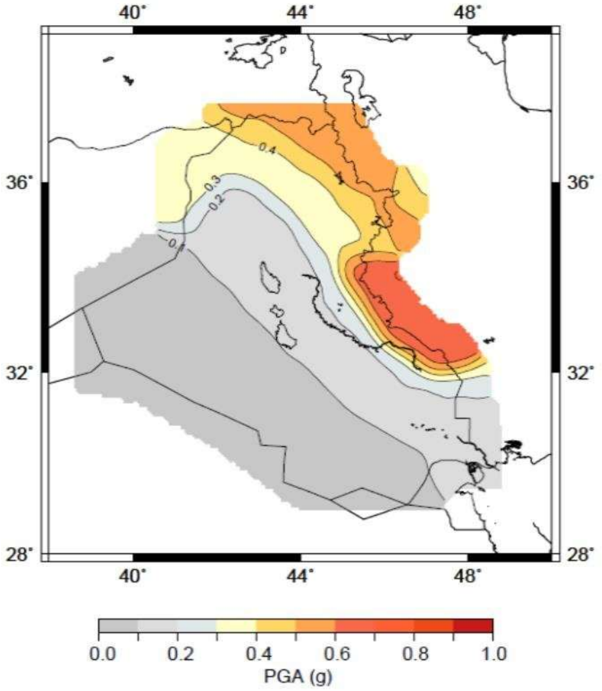

Figure 8: PGA map of Iraq.

6. Conclusions

A numerical study was carried out to investigate the effect of seismic loading on an NATM tunnel and the results were shown and discussed. One can conclude from the previous findings the following:

- The tunneling process led to a maximum lateral displacement of 7.17 mm.
- The maximum settlement resulted from the overburden pressure was 30.38 mm.
- When the vertical seismic load was applied, it was found that most of the deformation that occurred within the tunnel was in the invert rather than the crown of the tunnel.
- The shape of the tunnel plays an important role in the distribution of stresses along the tunnel lining and will lead to different deformation conditions.
- The lateral seismic load resulted in a maximum lateral displacement that did not exceed 17 mm at the left side.
- The resulted lateral displacement was greater than the vertical displacement after excluding the settlement due to the excavation and tunneling process. This leads to the fact that tunnels are more secceptible to lateral loads than vertical loads.
- The maximum peak ground acceleration (PGA) was found to be 1.07g for a node at the center of the ground surface.

Acknowledgements

The authors express their thanks and appreciation to the staff of the Civil Engineering Department at the University of Baghdad for their help and support during conducting this study.

References

[1] A. Balasubramanian, "Tunnels-types and importance," *Technical report. Centre for Advanced Studies in Earth Science*, University of Mysore, March, 2014.

[2] D. Jones and C. B. T.-P. of B. B. M. Brischke, Eds., "5 - Performance of the bio-based materials," Woodhead Publishing, 2017, pp. 249–333.

[3] Encyclopedia Britannica. 2021. Seismic wave. [online] Available at: <https://www.britannica.com/science/seismic-wave> [Accessed 8 May 2021].

[4] G. Tsinidis et al., "Seismic behaviour of tunnels: From experiments to analysis," Tunneling and Underground Space Technology, vol. 99, no. December 2019, p. 103334, 2020, doi: 10.1016/j.tust.2020.103334.

[5] J. A. Kadhim and A. O. Dawood, "Seismic performance of clay bricks construction," Civ. Eng. J., vol. 6, no. 4, pp. 785–805, 2020, doi: 10.28991/cej-2020-03091508.

[6] J. J. Wang, "Seismic design of tunnels. William Barclay Parsons Fellowship Parsons Brinckerhoff Monograph 7," no. June, pp. 1–159, 1993.

[7] L. M. Gil, E. Hernández, and P. De la Fuente, "Simplified transverse seismic analysis of buried structures," Soil Dyn. Earthq. Eng., vol. 21, no. 8, pp. 735–740, 2001, doi: 10.1016/S0267-7261(01)00039-2.

[8] M. Hassanlourad, M. Naghizadehrokni, and V. Molaei, "A Numerical Study of Seismic Response of Shallow Square Tunnels in Two-Layered Ground," *Int. J. Geol. Environ. Eng.*, vol. 13, no. 3, pp. 167–174, 2019.

[9] M. H. El Naggar and K. Bentley, "Dynamic analysis for laterally loaded piles and dynamic p-y curves," *Can. Geotech. J.*, vol. 37, pp. 1166–1183, Jan. 2011, doi: 10.1139/cgj-37-6-1166.

[10] M. H. Fasihnikoutalab, B. B. K. Huat, A. Asadi, and S. Daneshmand, "Numerical stability analysis of tunnel by PLAXIS," *Electron. J. Geotech. Eng.*, vol. 17 D, no. October, pp. 451–461, 2012.

[11] M. Power, D. Rosidi and J. Kaneshiro, "Seismic vulnerability of tunnels-revisited," *American Tunneling Conference*. 1998, Elsevier, Long Beach, CA, USA.

[12] Q. Lu, S. Chen, Y. Chang, and C. He, "Comparison between numerical and analytical analysis on the dynamic behavior of circular tunnels," *Earth Sci. Res. J.*, vol. 22, no. 2, pp. 119–128, 2018, doi: 10.15446/esrj.v22n2.72248.

[13] Science Learning Hub. 2021. Seismic waves. [online] Available at: <https://www.sciencelearn.org.nz/resources/340-seismic-waves> [Accessed 8 May 2021].

دراسة عددية عن سلوك أنفاق **NATM** تحت التحميل الزلزالي

حيدر علي المرزه [1]،* ***مهدي عبيد كركوش*** [2]

[1] *قسم الهندسة المدنية، جامعة بغداد، بغداد، العراق، h.almirza1901m@coeng.uobaghdad.edu.iq*

[3] *قسم الهندسة المدنية، جامعة بغداد، بغداد، العراق، Mahdi_karkush@coeng.uobaghdad.edu.iq*

* *الباحث الممثل : حيدر علي المرزه، email: h.almirza1901m@coeng.uobaghdad.edu.iq*

نشر في: 30 ايلول 2022

الخلاصة – أصبحت ضرورة الأنفاق أكثر أهمية في العالم الحديث بسبب أغراضها المختلفة واستقلال الحياة السطحية على الرغم من شكلها. يهدف هذا البحث إلى فحص سلوك نفق NATM المحمّل بالزلازل والموضوع في تربة حصوية جيدة التدرج. تم الحصول على اعلى إزاحة ناتجة عن ضغط التربة والتي كانت 30.38 مم بالإضافة إلى الإزاحة الرأسية والجانبية بحد أقصى 53 مم و 17 مم على التوالي. تم العثور على أعظم تعجيل ارضي (PGA) لتكون طبيعية عند مقارنتها بخريطة PGA للعراق.

الكلمات الرئيسية – نفق, انفاق NATM, التحميل الزلزالي, تحليل عددي, تربة.