

Seismic Response of Double Metro Tunnels Built in Deep Soft-Soil

Guy Ange N'goran Ehouman^{1*} Zhang Jing-Li¹

1. School of Civil Engineering and Architecture, Zhejiang University of Science and Technology, No.318, Liu-he Road, Hangzhou, Zhejiang Province, 310023, China
2. School of Civil Engineering and Architecture, Zhejiang University of Science and Technology, No.318, Liu-he Road, Hangzhou, Zhejiang Province, 310023, China

* E-mail of the corresponding author: guyangengoran@gmail.com

Abstract

Rapid development and urbanization have led to the use of underground structures along the world for a wide range of applications including tunnel for subways, railways, highways, material storage, sewage and water transport. The safety of these facilities during seismic events such as recent earthquake in Japan, Taiwan and Turkey becomes more and more problematic due to the complex soil-structure interaction (SSI). The major factor causing severe damages to metro structures is the large deformations imposed by surrounding soils. Thus, for a subway tunnel structure embedded in the soft soil, the study of nonlinear dynamic response of soil-structure interaction during earthquake is important. Nowadays, numerous tools of Finite Element (FE) analysis has been developed to simulate and analyse the tunnel behaviour in order to mitigate its damages during seismic events. In this paper, the displacement response of double metro tunnels under two different earthquake waves is investigate using a Finite Element program (ABAQUS) in 2D plane strain condition, by means of nonlinear dynamic behaviour of soil and tunnels in three different working conditions by varying the embedded depth of the tunnels in soil. The results show that the displacement response of double tunnels built in soft soil is related to the characteristics of the input ground motion, the nature of surrounding soil and the buried depth of the tunnel structures, the peak ground acceleration (PGA) and the SSI effect has an important influence on the displacement response of tunnel structures.

Keywords: double metro tunnels, soft soil, nonlinear, dynamic analysis, ground motion, displacement response, SSI, FE, PGA, ABAQUS

DOI: 10.7176/ISDE/12-2-04

Publication date: June 30th 2021

1. Introduction

The development and utilization of underground space becomes a new era hot issue for civil engineering in the 21st century. Among them, the subway is one of the mean vehicles of people's daily travel, and the seismic performance requirements for its structure is particularly high ^[1]. In the past, seismic design of underground structures have received considerably less attention than that of surface structures because of two reason. Firstly, because in the early stage of underground engineering construction, it was considered that the underground structures were buried in the rock and soil layer their influence on earthquake was very small and also, the surrounding rock and soil layer constitute a natural protective layer. Secondly, because at that time, there is significantly less information available for the design of underground structures ^[2-3-4]. But in recent large earthquakes event including the 1995 Kobe, Japan earthquake, the 1999 Chi-Chi, Taiwan earthquake and the 1999 Kocaeli, Turkey earthquake in which subway stations, tunnels and utility tunnels have experienced a significant number of damage shaken underground engineering and brought a great impact to this traditional concept, which changed that perception of earthquake workers ^[5]. Several researches has been carry out along the world including Dowding C. R., 1978, Owen, 1981, GN, Sharma, 1991, Wang W. L., 2001 and Wang ZZ, 2009 and more than 192 case studies ^[6-7-8-9] were considered and studied with the following objectives (1) attenuation relationship (2) magnitude and epicenter distance and (3) Peak ground acceleration. And these different works yielded the following conclusion:

- The ovaling effect on circular tunnels and racking effect on rectangular tunnels are found to be highly dependent on the relative stiffness between the tunnel lining and the surrounding ground, which makes the soil-structure interaction one of the most important factors in the seismic design and evaluation for tunnel structures.
- Tunnels built in rock medium responded with a little damage with a peak acceleration below 0.4g,

- Cut and cover tunnels and shallow tunnels tend to be more vulnerable,
- Deeper tunnels seems to be safer and damages are increased with the earthquake magnitude and decrease epicenter,
- Damages to tunnel are less with PGAs less than 0.2g whiles damages with PGAs between 0.2g-0.5g incurred slightly too heavy damages.

This present research work will focus specially on the displacement response of double metro tunnels system under earthquake loading. To do so, a 2D Finite Element Module will be developed in plane strain condition using ABAQUS Software to model the nonlinear dynamic behaviour of soil and double tunnels. The analysis will be conducted in three different working conditions by varying the depth of the tunnel structures. At the end of simulations, the results will be compared and studied.

2. Outline of the Problem

The Nanjing line 1 runs mainly in a north-south direction. The line starts at Magaoqiao station in the north, heading southwest to CPU (China Pharmaceutical University). The construction of the line 1 began in the year 2000 and was inaugurated on September 3, 2005, with sixteen stations and a length of 21.72 kilometers (13.50 mi). 14.33 km of the line track runs underground while 7.39km of the track run on or above ground. In fact, the structure is built in a thick soft soil ^[10] and the depth of line 1 is from 9m-14m when the metro line is transferred from underground to the ground and the thickness of the over bedding soil layer is small. For this reason, this study will consider three working conditions (3m, 9m, and 14m). The tunnel lining has a thickness of 0.7m, the external and internal diameters are respectively 5.5m and 6.2m. The thickness of the duct pieces is 35cm, and the metro concrete is C50. The shaking damages of earthquake event on a metro line are characterized by the overburden depth and the properties of the surrounding soil. The larger deformation of the surrounding soil cause severe damages to metro tunnel because the inertia of the surrounding soil is larger relative to the structure and in an event of seismic loading the soil-metro structure interaction cannot be neglected.

3. Modelling and the Parameters Selected

3.1 Finite element model of subway tunnel and soil

In this study, a 2-D finite element model will be developed in plain strain by using ABAQUS software. The tunnels lining are chosen as a reinforce concrete with a circular shape and the ground is modelled with ten horizontal soil layer profiles. The soil dimensions are (100*61), respectively as horizontal and vertical distances. The tunnels are assumed to be constructed in three different overburden depth, 3m, 9m, and 14m, which leads to three working conditions. The vertical distance between the two tunnels is 13m and the numerical analysis of the soil and the metro tunnel is modelled using ABAQUS user subroutine to define the material properties to account for the nonlinear dynamic behaviour of the soil and the metro tunnel during earthquake loading. The module is meshed with CPE4R element type with quadrilateral element shape and a pressure of 20kpa is applied uniformly at the top of the ground surface. Two different earthquake waves are applied in the horizontal direction at the bedrock of the soil profile with three different peak accelerations. Then, the dynamic implicit analysis is conducted with ABAQUS software to simulate the model. Fig.1, and Fig.2 show the finite element mesh of the soil and tunnel lining.

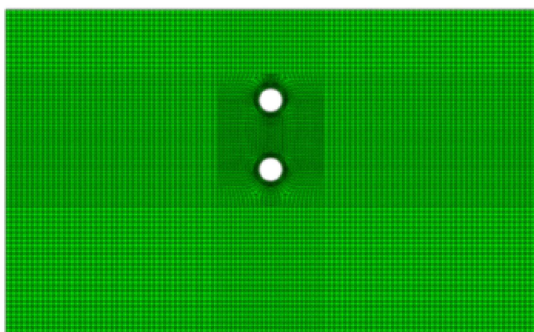


Figure1. Finite element mesh of soil

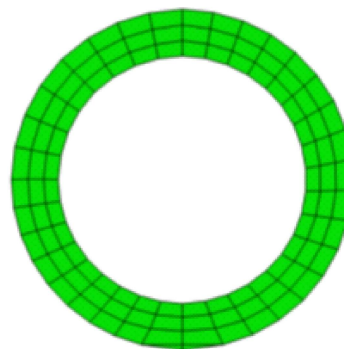


Figure2. Finite element mesh of tunnel

3.2 Parameters and constitutive model of materials

Table1. Concrete Tensile Behaviour

Yield stress (kN/m ²)	Displacement (mm)
2900	0
2020	5.52E-05
1410	1.03E-05
979	1.45E-04
682	1.83E-04
475	2.19E-04
330	2.53E-04
230	2.86E-04
160	3.18E-04
112	3.50E-04
77.6	3.81E-04
54.1	4.11E-04
37.6	4.42E-04

Table2. Concrete Compressive Behaviour

Yield stress (kN/m ²)	Compressive strain
4690	0
6830	0.001

Table3. Soil Constitutive Parameters

Soil no	Thickness	Soil description	Gravity KN/m ³	Young Modulus (MPa)	Poisson Ratio	Shear wave Velocity (m/s)	Friction angle Φ
1	2.0	Mucky soil	19.0	1.0	0.45	114	16
2	2.0	Mucky silty	17.8	1.0	0.45	129.1	16
3	4.0	Silt and sand	19.0	5.2	0.35	152.7	26
4	3.0	Mealy sand	20.5	7.5	0.30	137.1	30
5	3.0	Mucky soil	19.3	2.1	0.45	128.5	16
6	9.0	Fine sand	18.9	10.0	0.30	172.7	27
7	12.5	Silt-fine sand	21.2	11.1	0.32	205.8	30
8	10.3	Fine sand	18.9	11.7	0.30	236.3	27
9	5.2	Mealy sand	20.5	12.0	0.32	263.2	30
10	10.0	Clay	19.3	3.2	0.42	491.6	21

4. Boundary Condition

The boundary conditions as adopted for double tunnels analysis in this study is made so that, the wave refraction and reflection of the vertical model boundaries can be avoided. According to Meissner (1996), the choice of sufficient mesh dimension is made so that, the stresses at the model boundaries should not be influenced by the tunnel excavation, and therefore, recommends the use of (4-5) times the tunnel diameter from the tunnel center

line to the vertical mesh boundaries and (2-3) times from the tunnel center point to the bottom boundary. For the vertical boundaries, the horizontal displacement/rotation is restrain and the vertical displacement/rotation is left free. The bottom boundary has total fixities restraining both horizontal and vertical displacements/rotation. The upper horizontal boundary has no fixities and is left free to displace.

5. Earthquake Wave Selection

In this present study, two-time histories earthquake acceleration wave are used for the analysis. The first one is the El Centro acceleration recorded during the 1940, Imperial Valley Earthquake [11] and the second one is the Taft acceleration recorded during the 1952, Kern County, California Earthquake [12]. Fig 3.7 shows the unscaled acceleration time history of the two selected waves (El-Centro and the Taft input wave). The input acceleration is scaled into three peaks ground accelerations 0.053g, 0.116g and 0.154g to simulate the probability of exceedance 63%, 10%, 3% in 100 years of the site.

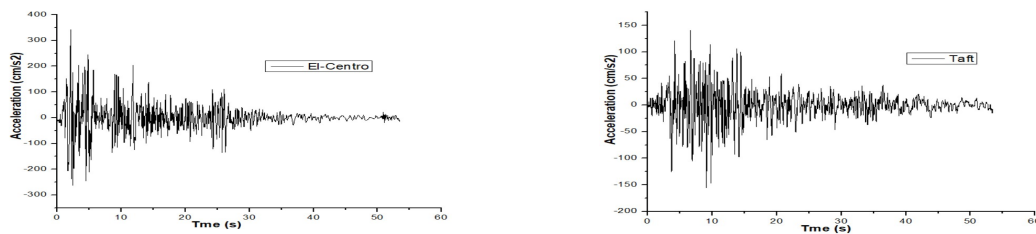


Figure3. El-Centro and Taft wave unscaled acceleration time histories.

5. Result and Analysis of horizontal displacement

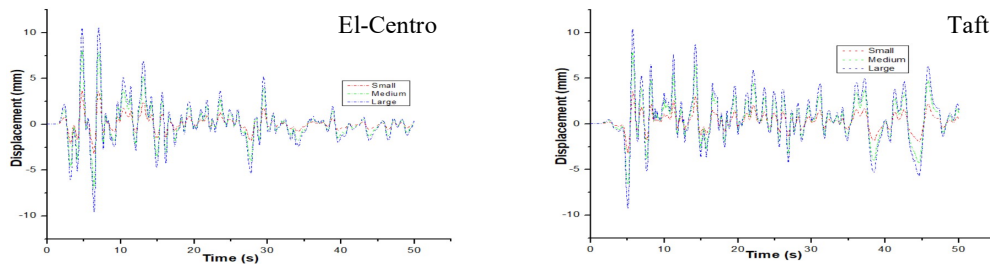


Figure4. Horizontal relative displacement time histories between the top and bottom of the upper tunnel in first working condition with El-Centro and Taft input.

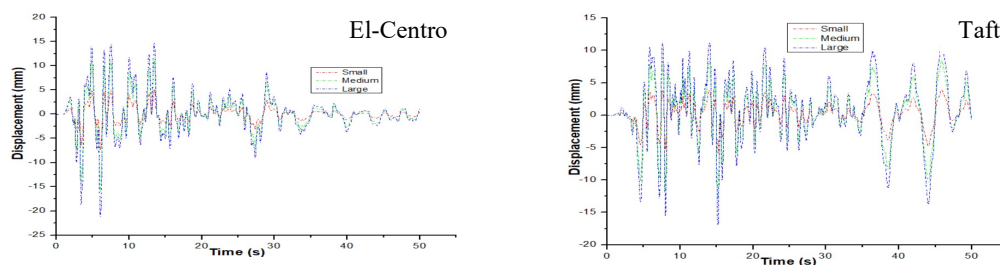


Figure5. Horizontal relative displacement time histories between the top and bottom of the lower tunnel in first working condition with El-Centro and Taft input.

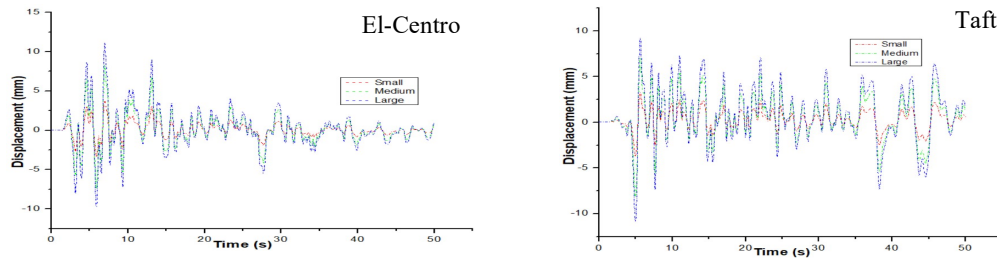


Figure6. Horizontal relative displacement time histories between the top and bottom of the upper tunnel in the second working condition with El-Centro and Taft input.

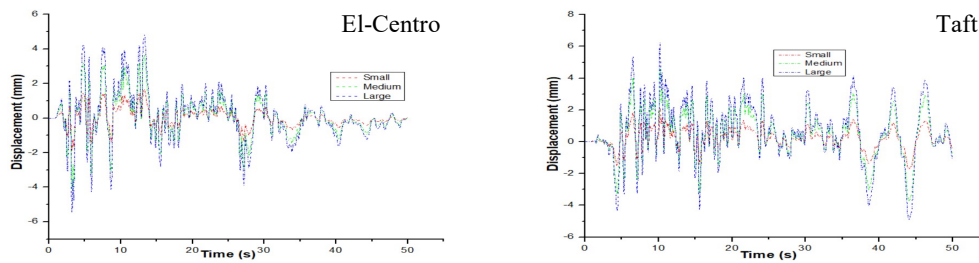


Figure7. Horizontal relative displacement time histories between the top and bottom of the lower tunnel in the second working condition with El-Centro and Taft input.

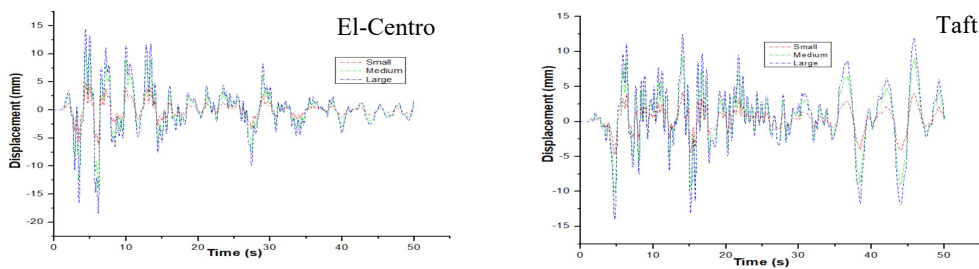


Figure8. Horizontal relative displacement time histories between the top and bottom of the upper tunnel in third working condition with El-Centro and Taft input.

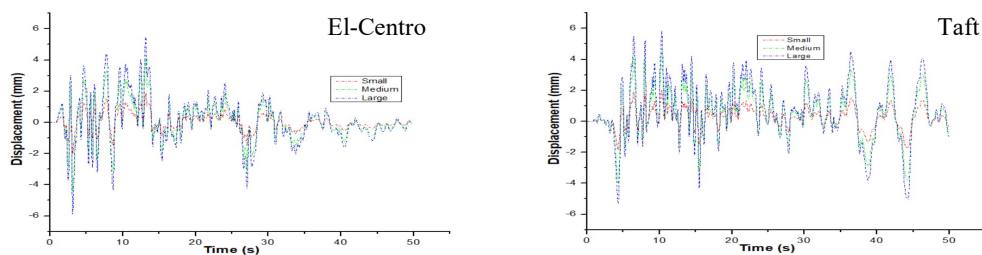


Figure.9 Horizontal relative displacement time histories between the top and bottom of the lower tunnel in third working condition with El-Centro and Taft input.

Fig.4 to 9 show the horizontal relative displacement of double tunnels in three different working conditions with two different input waves (El-Centro and Taft waves) scaled at 0.053g, 0.116g and 0.154g. The first working condition is 3m depth, the second is 9m depth and the third is 14m depth. The figures show an increase in relative displacement with the lower tunnel then the upper one under the two input waves in the first working condition. The relative displacement in this condition is large with El-Centro input. In the second working condition, figures show an increase in relative displacement with the upper tunnel then a decrease with the lower one under the two input waves. In the third working condition, figures show an increase in relative displacement with the upper tunnel then a decrease with the lower one under the two input waves.

Table5. Maximum relative displacement under different working condition

Input Wave			3m Depth		9m Depth		14m Depth	
			ΔS (mm)	ζ	ΔS (mm)	ζ	ΔS (mm)	ζ
Upper Tunnel	Small	El-Centro	3.694	1.019	3.820	1.029	6.381	1.326
		Taft	3.627		3.711		4.814	
	Medium	El-Centro	8.016	1.015	8.331	1.021	13.947	1.324
		Taft	7.894		8.157		10.534	
	Large	El-Centro	10.613	1.018	11.110	1.023	18.467	1.318
		Taft	10.425		10.865		14.008	
Lower Tunnel	Small	El-Centro	7.375	1.258	1.876	0.884	2.034	1.014
		Taft	5.862		2.122		2.005	
	Medium	El-Centro	16.111	1.258	4.097	0.879	4.451	1.013
		Taft	12.803		4.659		4.394	
	Large	El-Centro	21.345	1.257	5.437	0.876	5.910	1.011
		Taft	16.979		6.207		5.844	

Table6. Depth influence coefficient El-Centro wave

Depth		El-Centro Input					
		Small		Medium		Large	
		Δs (mm)	ξ	Δs (mm)	ξ	Δs (mm)	ξ
Upper Tunnel	3m	3.694	/	8.016	/	10.613	/
	9m	3.820	0.967	8.331	0.962	11.110	0.955
	14m	6.381	0.599	13.947	0.597	18.467	0.602
Lower Tunnel		Δs (cm)	ζ	Δs (cm)	ζ	Δs (cm)	ζ
	3m	7.375	/	16.111	/	21.345	/
	9m	1.876	3.931	4.097	3.932	5.437	3.926
	14m	2.034	0.922	4.451	0.920	5.910	0.920

Table7. Depth influence coefficient Taft waves

Depth		Taft Input					
		Small		Medium		Large	
		$\Delta s(\text{mm})$	ξ	$\Delta s(\text{mm})$	ξ	$\Delta s(\text{mm})$	ξ
Upper Tunnel	3m	3.627	/	7.894	/	10.425	/
	9m	3.711	0.997	8.157	0.968	10.865	0.960
	14m	4.814	0.771	10.534	0.774	14.008	0.776
Lower Tunnel		$\Delta s(\text{mm})$	ζ	$\Delta s(\text{mm})$	ζ	$\Delta s(\text{mm})$	ζ
	3m	5.862	/	12.803	/	16.979	/
	9m	2.122	2.762	4.659	2.748	6.207	2.735
	14m	2.005	1.058	4.394	1.060	5.844	1.062

Table5, 6 and 7 show the maximum horizontal relative displacement of upper and lower tunnels under different working condition and the depth influence coefficient of El-Centro and Taft waves respectively. The depth influence coefficient is defined as the horizontal relative displacement when embedding depth is 3m over that of 9m embedding depth and when the embedding depth is 9m over that of 14m embedding depth.

From horizontal displacement time history curves, the comparison analysis of maximum relative displacement and depth influence coefficient, we can make the following interpretations:

* By comparing the horizontal relative displacement under two different earthquake waves (El-Centro and Taft), the results show that the relative displacement of the metro tunnel with El-Centro input is larger than the relative displacement in Taft case. This indicates that the earthquake response of metro tunnel is related to the characteristics of the input ground motion.

*By Comparing the relative displacement between the top and bottom of the tunnels under the three working conditions, (3m, 9m, and 14m), it appears that the horizontal relative displacement is maximum in the first working condition when the embedding depth is 3m. Also, from comparative results of the relative displacement between the top and bottom of the upper and lower tunnels, it can be seen that the upper tunnel displays the largest relative displacement except in the first working condition (3m depth). These result indicate that the buried depth of tunnel structure and the nature of soil around have a great influence on tunnel displacement response.

* For a specific working condition with the same embedding depth, the increase of the peak ground acceleration leads to an increasing of the horizontal relative displacement between the top and bottom of the tunnel structure. The maximum relative displacement appears between 5~7s when inputting El-Centro waves, and between 14~16s when inputting Taft waves. When the depth is small, the depth influence coefficient ξ is large. Indeed, these results mean that the displacement response of tunnel structure is sensitive to the peak ground acceleration and the SSI effect has an important influence on tunnel response.

6. Summary

In this paper, the horizontal displacement response of double tunnel structures built in thick soft soil at different embedded depth and subjected to two different earthquake waves is investigated. Based on the results of the displacement curves, the following conclusions can be established: (1) the seismic response of metro tunnels built in soft soil is related to the characteristics of the input ground motion. (2) The nature of surrounding soil and the buried depth of the tunnel structure have a great influence on the displacement response metro tunnel; increase the buried depth help to improve the safety of tunnel structure. (3) The peak ground acceleration and the SSI effect have an important influence on the displacement response of tunnel structure.

As future works perspective, we plan to:

- (1) Develop a single model of metro tunnel with the same conditions as the double tunnels, and both results will be compared and studied.
- (2) Develop a model by varying the poisons ration and the friction angle to investigate their influence on such structures when subjected earthquake loading.

(3) Develop a model by adopting different diameters in order to investigate on the role that plays the thickness of tunnel lining during seismic shaking.

References

- [1] Sakyi, K.S., Benjamin, K., Godson, k. (2018), “Seismic Response Analysis of Underground Structures”*J. Enviro. Earth Sci* 8 (5), 48.
- [2] Zhixin Z and Jiren X 2003 *J. In 1995 the Japanese earthquake in Kobe building collapse and the edge of the S wave and surface wave interference on the secondary Basin. Chinese Science Bulletin.* 48 2566.
- [3] Wang, J.N., 1993. *Seismic Design of Tunnels, A State-of-the-Art Approach. Monograph 7, Parsons Brinkerhoff Quade and Douglas, Inc., New York.*
- [4] Youssef MA Hashash, Jeffrey J Hook, Birger Schmidt, I John, Chiang Yao. *Seismic design and analysis of underground structures, (Tunneling and underground space technology).* p248.
- [5] Longjun X and Lili X 2005 *J. Some considerations on the physical measure of seismic intensity. Acta Seismologica Sinica.* 27 656.
- [6] Dowding, C.H., Rozen, A., 1978. *Damage to rock tunnels from earthquake shaking. J. Geotech. Eng. Div., ASCE* 104, (2), 175-191.
- [7] Sharma S, Judd WR (1991) *Underground opening damage from earthquakes. Engineering Geology.* 30 (3-4), 263–276
- [8] Wang WL, Wang TT, Su JJ, Lin CH, Seng CR, Huang TH (2001), *Assessment of damage in mountain tunnels due to the Taiwan Chi-Chi earthquake. Tunnel Underground Space Technology*16, (3), 133–150.
- [9] Wang, J.N., and Munfakh, G.A. (2001), “*Seismic Design of Tunnels*”, *WIT Transaction on the Built Environment* 57.
- [10] WIKIPEDIA. Retrieved from https://en.wikipedia.org/wiki/Line_1,_Nanjing_Metro
- [11] Ground-Motion Virtual Data Center (VDC), El-Centro Earthquake Wave. Retrieved from https://strongmotioncenter.org/vdc/waveform_data/smdb/1940/c/139u37el.c0a
- [12] Ground-Motion Virtual Data Center (VDC), Taft Earthquake Wave. Retrieved from https://strongmotioncenter.org/vdc/waveform_data/smdb/1952/c/203e53ta.f0a