ANALYSIS OF NATM TUNNEL RESPONSES DUE TO EARTHQUAKE LOADING IN VARIOUS SOILS

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ABSTRACT

Tunnels play a large part in the redevelopment of urban areas. In almost all urbanized areas it is hard to avoid building in close proximity to previously constructed building. Many of these urban areas also lie in close proximity to water, in which weaker soils prevail. Some of these areas, also, are prone to frequent earthquakes. It is necessary, therefore, for these areas to implement standard tunneling techniques. The New Australian Tunneling Method (NATM), which addresses the concerns listed above, is becoming increasingly popular and has been adopted by some countries as the preferred method of tunneling. The NATM is a method that incorporates the surrounding rock or soil into a ring-like support for the structure. With the growing popularity of this method, it is necessary to determine which soils are best suited for this method of tunneling. In this project the soils of various cities will be analyzed to determine which of the soils perform better with the NATM using a two dimensional model of the tunnel that is being exposed to earthquake excitations.

KEYWORDS

New Australian Tunneling Method (NATM), earthquake, finite elements.

PROBLEM STUDIED

There are several reasons for utilizing tunnels. They can be used to connect land masses, to bypass impeding geologic formation, or stability issues, and to reduce environmental concerns. Most tunnels, however, are used to increase the flow of traffic. Fifty percent of the world's population live in urban areas and seventy percent of the population live in earthquake prone areas (Merritt, et al. 1985). Initially, tunnels were designed with no regard to seismic effects, but, recently, there has been enhanced awareness of seismic hazards for underground structures (Merritt, et al. 1985).

There are two broad categories of earthquake effects of tunnels: ground shaking and ground failure. When seismic waves propagate through the earth's crust, the resulting ground motions are considered ground shaking. There are two basic categories of ground shaking. Body waves travel within the earth's inner layers. These waves can be either longitudinal P or transverse shear S waves. P waves move in a compressional motion similar to the motion of a slinky, while the S waves move in a shear motion perpendicular to the direction the wave is travelling. These waves can travel in any direction underground. Surface waves travel along the earth's surface in the same matter a ripple would travel through water. These waves can either be Rayleigh or Love waves. Love waves shake the surface side-to-side. Rayleigh waves move the surface of the earth around in a circle, forward and down then back and up. This is the same as the motion in an ocean wave (Merritt, et al. 1985). Any tunnel structure will be deformed as the ground is deformed by the traveling waves.

Ground failure can include different types of ground instability. These can include faulting, liquefaction, and tectonic uplift and subsidence. Faulting occurs when an increase in stress causes rocks to break. Liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading. Tectonic uplift and subsidence is the upward and downward movement of the ground due to plate movement. These phenomena have been responsible for tremendous amounts of damage in historical earthquakes around the world. Each of these hazards could possibly be detrimental to tunnel structures (Merritt, et al. 1985).

Many tunneling methods are in common use, and a suitable one is generally chosen according to geology, tunnel dimensions, and other factors (Kirzhner and Rosenhouse 2000). The New Australian is a method in which, after a section of tunneling is completed, shotcrete is applied to the surface of the tunnel and the surrounding rock or soil becomes integrated into the support structure (Yang, 2002). Extreme care is taken during excavation and immediate application of support media prevents unnecessary loosening of soil. These tunnels use rounded tunnel shapes to prevent stress concentrations in corners where most failure mechanisms start (Yamaji, 1998). These tunnels, also, utilize thin linings to minimize bending moment. Observation of tunnel behavior during construction is an important part of NATM. This optimizes working procedures and support requirements (Yang, 2002). Many countries have adopted this method as the primary method of construction.

OBJECTIVE

The objective of this project is to determine which soil types, when used in conjunction with a tunnel completed using the New Australian Tunneling Method, perform better when subjected to seismic excitation. For this purpose, soils from seven cities were selected and a finite element model of the tunnel created for each case. Comparisons based on the maximum displacement each soil experienced when subjected to an earthquake were then made.

RESEARCH APPROACH

The first step was to identify the physical problem. This included describing the physical structure, identifying the source of dynamic excitation, and determining the expected outcomes. The next step in the process was defining the inputs and then defining the model based on the inputs. The last step was to find the solution of the model and review the results of the project.

The world cities selected for this project were:

- Agadir, Morocco
- Avezzano, Italy
- Chimbote, Peru
- Los Angeles, California
- Mexico City, Mexico
- Tangshan, China
- Tokyo, Japan

There were four basic criteria used to select the cities used for this project. The first criterion was the earthquake history of the city. It was necessary to use cities that were susceptible to large magnitude earthquakes. The next criterion was the population of the city to evaluate the possibility of tunnel use, which is the third criterion. Tunnels are more likely to be used in cities that have a large population. The last criterion used was the variance in the soil types present in these areas. It was necessary to select cities with contrasting soils to obtain a broad range of results.

There are currently15 different soil orders present in the world (Yamaji, 1998). Each city used in this experiment was classified by soil order. That soil order was then classified by the aggregate(s) associated with them as shown in Table 1.

Table 1. Soil order and soil types.

Location	Soil Order	Soil Type
Agadir, Morocco	Alfisols	Low Plasticity Clay
Avezzano, Italy	Ultisols	Low Plasticity Silt
Chimbote, Peru	Entisols	Gravel-Sand Mixture
Los Angeles, California	Mollisols	Organic
Mexico City, Mexico	Andisols	Medium Plasticity Silt
Tangshan, China	Inceptisols	Sandy Gravel
Tokyo, Japan	Oxisols	High Plasticity Clay

The specific properties of each soil are listed in Table 2. This properties listed are needed to in the calculations for each city.

Table 2. Soil Properties.

	Soil Type	Mass Density (kg/m^3)	Elastic Modulus (Pa)	Poisson's Ratio	Internal Friction Angle (deg.)	Cohesion (Pa)
Gravel	Uniform	1600	4.00E+07	0.25	34	0
	Sandy w/ few fines	2100	4.00E+07	0.25	35	0
	Sandy w/ silt or clay	2100	4.00E+07	0.25	35	1000
	Mixture of gravel and sand	2000	1.50E+07	0.25	38	3000
Sand	Uniform, fine	1600	1.50E+07	0.25	32	0
	Uniform, coarse	1600	2.50E+07	0.25	34	0
	Uniform, well-graded	1800	2.00E+07	0.25	33	0
Silt	Low plasticity	1750	4.00E+06	0.25	28	2000
	Medium to high plasticity	1700	3.00E+06	0.25	25	3000
Clay	Low plasticity	1900	2.00E+06	0.28	24	6000
	Medium plasticity	1800	1.00E+06	0.25	20	8000
	High plasticity	1650	6.00E+05	0.25	17	10000
	Organic	1550	5.00E+05	0.25	20	7000
Rock	Granite	2700	7.40E+10	0.25	51	5.51E+07

The physical structure used for this simulation consisted of a tunnel surrounded by two ground layers, each 130 meters wide (Figure 1). The bottom layer was granite rock and was 106 meters in height. The properties for this layer remained constant during each trial The uppermost layer was a 24 meter deep soil layer that changed according to the soil properties associated with each trial city. The tunnel was circular with a 22 meter diameter and was buried 67 meters below the ground surface.

Finite element method was used in this project. This method is used to model and solve complex two and three dimensional engineering problems. The Visual Finite Element Analysis (VisualFEA) program incorporates powerful finite element processing software with a user-friendly graphical interface that reduces the amount of time needed for programming.

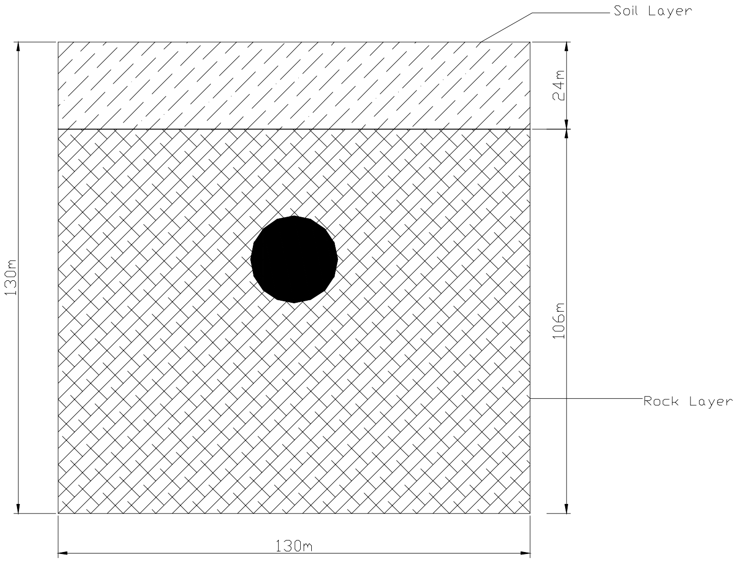

Figure 1. Physical Structure.

First a two dimensional plane strain model was used. This is used in modeling three dimensional structures that are uniform throughout their length, e.g. beams and cylinders. The data was taken from a point between the rock and soil interface directly above the highest point of the tunnel (Figure 2).

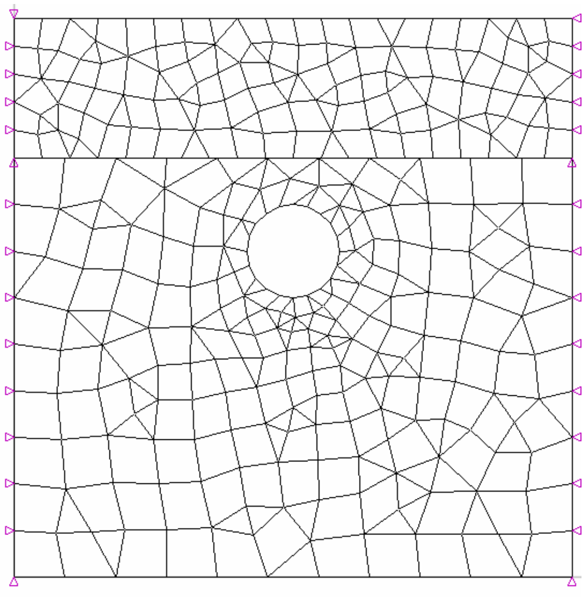

Figure 2. VisualFEA structure.

Fixed vertical ends were used to restrict the movement of the ends of the model. A damper was placed at the bottom boundary to keep it from moving uncontrollably. For this model Rayleigh damping of 0.05 was used to model the natural damping characteristics of the rock and the soil.

The source of dynamic excitation used in this project was the acceleration record for the 1995 Kobe, Japan earthquake, as shown in Figure 3.

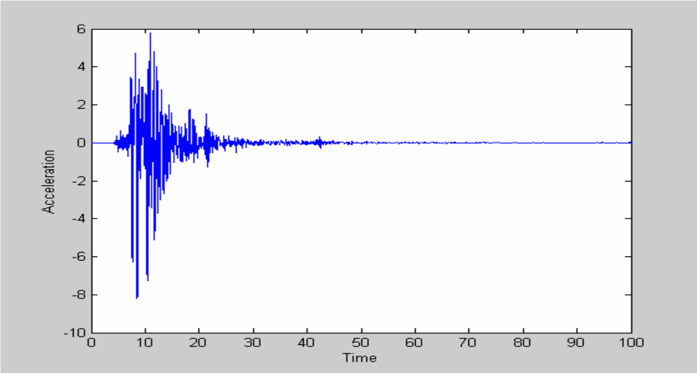

Figure 3. Acceleration record of the 1995 Kobe earthquake, Japan).

This earthquake data was used because this earthquake was the most devastating to civil infrastructure in recorded history. The acceleration input from the earthquake was applied to the bottom boundary.

OUTCOMES

Since there are thirteen different soil types, the recorded data from uniform gravel and medium to high plasticity silt are evaluated for comparison purpose.

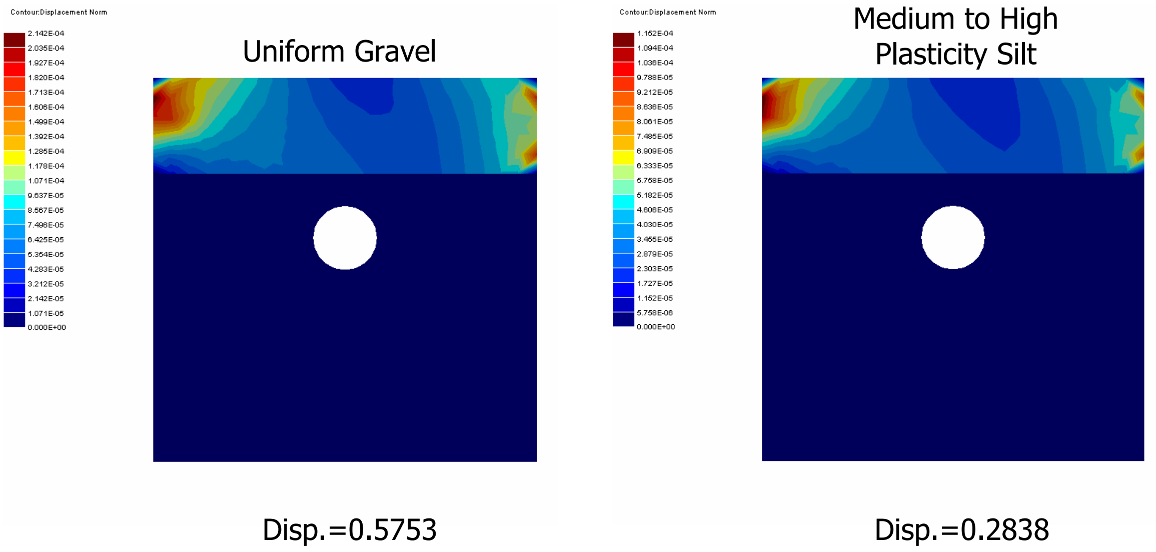

Figure 4. Graphical Results for Uniform Gravel and Medium to High Plasticity Silt

Although the bands of color seem similar in their placement, their difference is relayed in the scales of each soil. The scale for uniform gravel goes from 0-2.1406 cm and the scale for medium to high plasticity silt only goes form 0-1.1526 cm.

The displacement results for all soils tested are listed in Table 3. For this project, it was found that soils containing between ten and fifty percent fine particles performed better under excitation than soils with smaller amounts of fine particles(<10%). Soils with the greatest amounts of fines (>50%) performed unfavorably as compared to the other soils. Soils that had a relatively low modulus of elasticity had a greater maximum displacement than other soils in the study. The best performing soils were in the gravel category. These soils performed better overall than sand, silt, or clay. The sand category performed the worst overall, although uniform sand had one of the lowest maximum displacements in all categories.

Table 3. Displacement results.

	Soil Type	**Maximum Displacement (cm)**
Gravel	Uniform	0.5783
	Sandy w/ few fines	0.5708
	Sandy w/ silt or clay	0.02057
	Mixture of gravel and sand	0.05604
Sand	Uniform, fine	1.5550
	Uniform, coarse	0.03947
	Uniform, well-graded	1.1515
Silt	Low plasticity	0.2129
	Medium to high plasticity	0.28385
Clay	Low plasticity	0.4304
	Medium plasticity	0.85182
	High plasticity	1.4148
	Organic	1.7049

The results for each city are presented in Table 4. Tangshan, China recorded the smallest maximum displacement for the point of interest. The maximum displacement was only 0.02057 cm. The location that recorded the highest maximum displacement was Tokyo, Japan, 1.419 cm. Although Tokyo has the highest maximum displacement, these displacements would only produce minor cracks in the tunnel structure (Yang, 2002). Using the model representing a NATM tunnel, it is shown that tunnels constructed using this tunneling method produces relatively small displacements under earthquake loadings and could possibly considered as the primary method of construction in other projects.

Table 4. Displacement results for selected cities

Location	Soil Type	Maximum Displacement (cm)
Agadir, Morocco	Low Plasticity Clay	0.4304
Avezzano, Italy	Low Plasticity Silt	0.2129
Chimbote, Peru	Gravel-Sand Mixture	0.05604
Los Angeles, California	Organic	0.1704
Mexico City, Mexico	Medium Plasticity Silt	0.2839
Tangshan, China	Sandy Gravel w/ Silt	0.02057
Tokyo, Japan	High Plasticity Clay	1.419

POSSIBLE FUTURE WORK

To increase the accuracy of this project, a three dimensional model with varying ground layers can be used. A water table can be introduced to simulate the possibility of liquefaction. Also, a structure that does not include a tunnel could be used for comparison with each soil type.

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