Dynamic Analysis of Underwater Tunnels

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ABSTRACT: Tunnels have become an important mode of transportation due to increase in population and density of traffic all over the world. An underwater tunnel is a tunnel which is partly or fully constructed under a body of water. Underwater structures are not absolutely immune against dynamic waves and are prone to damages. Thus it is significant to perform the dynamic analysis of underwater tunnels. In the present study, the dynamic behaviour of underwater single and twin tunnels are studied numerically with different tunnel materials. Study includes static and dynamic analysis of twin tunnel models with varying overburden, varying position along depth and varying spacing. The dynamic analysis is done adopting the load data of Kutch earthquake. It is observed that twin tunnels with varying overburden developed maximum stresses when compared with uniform overburden.
Keywords: Underwater Twin tunnels, Dynamic analysis, Numerical modelling.

1. INTRODUCTION

Tunnels are underground passageways, which is dug through the surrounding soil/earth/rock. It can be for foot or vehicular road traffic, rail traffic or a canal. An underwater tunnel is a tunnel which is partly or fully constructed under a body of water. They are often used where building a bridge or operating a ferry link is impossible, or to provide competition (or relief) for existing bridges or ferry links. The underwater tunnels are of two types: (i) underwater tunnel which is immersed under the water and is influenced only by buoyancy and hydrostatic pressure (ii) underwater tunnel which passes below the bed of the water body and is influenced by hydrostatic pressure and overburden pressure. The underground systems help to reduce the cost and project completion time when the acquisition of land is nearly impossible or moving surface utilities are expensive. Generally underground structures are safer than surface structures against dynamic waves. This is because surface structures are only connected to the ground from the lower surface and vibrate free whereas underground structures are completely connected to the surrounding environment and thus are more resistant to vibration. In spite of this, there are reports of damage to such structures due to dynamic waves. The long-term stability of tunnels is one of the most important factors in the design and implementation of underground spaces. Since tunnels and underground spaces can be subjected to dynamic loads like earthquakes and explosions during construction and operation stages, dynamic stability analysis of such structures is of great importance.

Collapse of a number of underground structures has occurred during various earthquakes (1995 Kobe, Japan earthquake, 1999 Chi-Chi, Taiwan earthquake and 1999 Duzce, Turkey earthquake). During the 1999 Duzce earthquake in Turkey, Bolu highway twin tunnels experienced a wide range of damage. Based on these collected details, it is understood that the study on the behavior of underground/underwater tunnels is of high significance. Moreover, the recently inaugurated Mumbai-Ahmedabad Shinkansen high speed rail route has around 7km undersea tunnel. Hence this study is focused on the dynamic behavior of twin tunnels subjected to earthquake loading.

Boldini et.al (2010) conducted one dimensional (1D) and two dimensional (2D) fully coupled finite element simulation to investigate the dynamic behaviour of circular tunnels in the transverse direction. Tiwari et.al (2016) reported parametric sensitivity studies adopting coupled Eulerian-Lagrangian (CEL) analysis tool in finite element software. Navarro (1992) reported seismic design of tunnels adotping FEM analysis by using numerical tool FLUSH. Anastasopoulos et.al (2007) used finite-element method to perform nonlinear dynamic transient analysis of the tunnel. Anitha Kumari et.al (2014) modeled twin tunnels with circular and horse-shoe cross sections to understand the effect of the shape of the tunnel and varying shallow overburden on the mechanical response when subjected to seismic loading. The literature review indicates that the studies reported on dynamic analysis of underwater tunnels especially twin tunnels are limited. The study is focused to analyze the response of underwater single and twin tunnels subjected to seismic loading followed by a parametric study under different conditions including depth from soil bed, spacing between tunnels, location of tunnels and materials used for tunnel.

2. NUMERICAL MODELLING OF UNDERWATER TUNNELS

De et al. (2017) studied the response of a tunnel subjected to blast loading through a combination of physical model tests utilizing a geotechnical centrifuge and numerical model analyses. The model tunnel was 760 mm long with an outer diameter of 76 mm and wall thickness of 2.5 mm. In all centrifuge tests the soil cover above the tunnel crown was kept constant at 38 mm. The centrifuge model consisted of a copper tunnel built to a 1:70 scale and it was tested at 70g acceleration. This represents a prototype with a length of 53 m, an outside diameter of 5.3 m, wall thickness of 0.133 m. The flexural stiffness (EI) of the tunnel was 13×10^6 kNm^2. The dimensions and the properties of water, soil and tunnel material for the current study are taken from this reported study. The dimensions of the tunnel model is shown in Table 1. Nevada soil properties is used for the study and the same is tabulated in Table 2. Since the tunnel is below the soil bed, the overburden pressure is calculated with the saturated density of the soil bed. The relative density of the soil is reported as 60%.

Table 1 Dimensions of the tunnel model (De et.al, 2017)

Variable	Value (m)
Length	53
Outer diameter	5.3
Wall thickness	0.133
Soil cover	2.7
Water cover	2.7

Table 2 Properties of Nevada sand

Variable	Value
Maximum dry density	17.33 kN/m^3
Maximum dry density	13.87 kN/m^3
Maximum void ratio	0.887
Minimum void ratio	0.511
Specific gravity	2.67

After fixing the dimensions, numerical modelling was done by using the CATIA software. The 3-D model developed in CATIA software was imported into Hyper mesh software for meshing. Models were developed for single and twin tunnels. The model is divided into a number of elements and nodes. 3-D hexahedral meshing was done using the software. Hexahedral or brick elements are solid elements which are extracted from 2D Quad elements. Hyper mesh builds around 8 to 20 noded hexa elements. The 3-D view of the twin tunnels modeled is shown in Figure 1. For the general cases, the optimum spacing between the tunnels is taken as 4 times diameter (4d) of the single tunnel. Soil is modeled using an eight noded element with three degrees of freedom at each node including translations in nodal x, y and z. This element type is referred to SOLID 185. There are two forms of SOLID 185 elements which are classified as homogeneous structural solid and layered structural solid. Since soil is considered as homogeneous, the element considered is homogeneous structural solid.

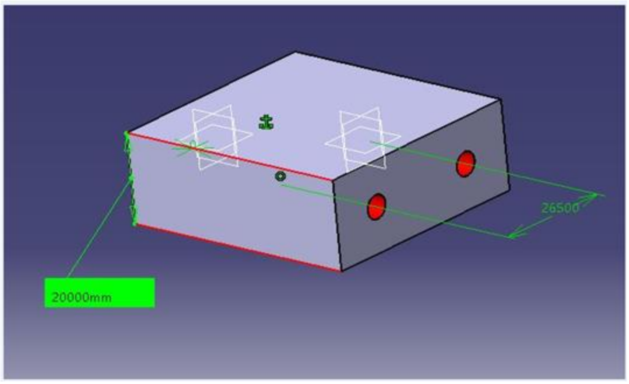

Figure 1 3-D view of the twin tunnel model

3. ANALYSIS OF UNDERWATER TUNNELS

The CATIA model was imported into ANSYS WORKBENCH for static and dynamic analysis. The model is confined from all the five directions and the pressures due to soil and water is applied onto the model corresponding to the depth of soil cover and water respectively.

3.1 Static analysis of underwater tunnels

A static structural analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed. After applying the overburden pressure, static analysis is performed on the underwater tunnel model made of copper, steel and concrete. In this case, the spacing between the tunnels is maintained as 4 times the diameter of the tunnel and the soil overburden is kept uniform. Figure 2 and 3 show the deformation and stress in concrete twin tunnels respectively when subjected to static loading. The material property of the tunnel model was changed to copper and steel and the analysis was done for the same boundary conditions and loading conditions.

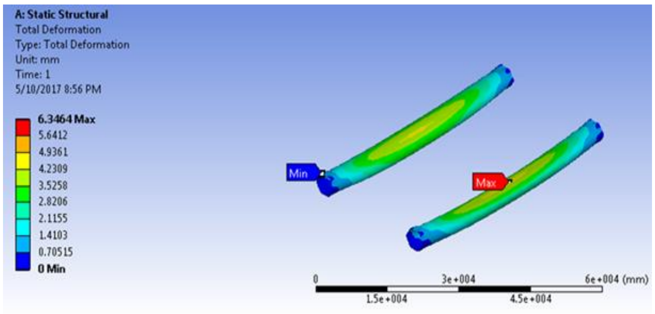

Figure 2 Deformation in concrete twin tunnels

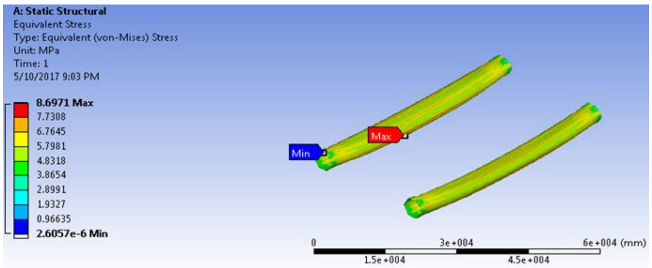

Figure 3 Stresses in concrete twin tunnels

3.2 Dynamic analysis of underwater tunnels

Kutch earthquake data, shown in Figure 4 was considered as the load for dynamic analysis.

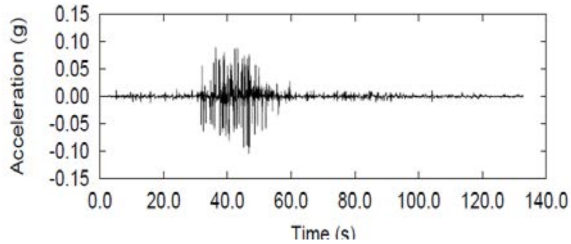

Figure 4 Kutch earthquake data (M. Shrikhande et.al, 2001)

In order to analyse the twin tunnel for seismic load, random vibration analysis was adopted. Through a Fourier analysis, the non-periodic acceleration data can be converted into a series of many overlapping sine waves, with each curve cycling at its own frequency and amplitude. Even though, acceleration amplitude constantly changes in the time-history data, the average value of all the amplitudes within a given frequency range can be determined to obtain the power spectral density (PSD) function. The PSD function was given as input to finite element software and the stress values on the twin tunnel were obtained with its probability of occurrence in a linear elastic framework.

Figure 5 shows the stresses developed in the twin tunnels when subjected to the given earthquake load. The probability of occurrence is 68.3%. The results of analysis of different cases with various materials indicate that the maximum deformation occurs along the spring line whereas the maximum stresses are observed at the crown of the tunnel.

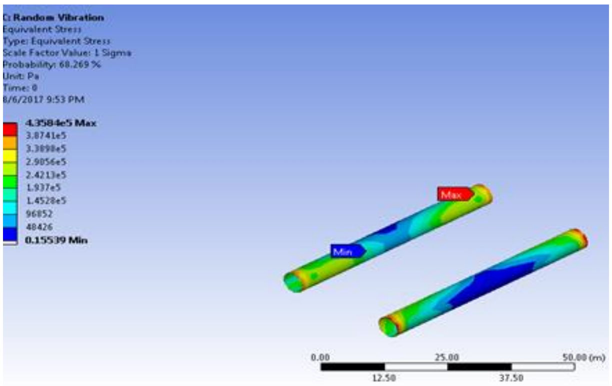

Figure 5 Stresses along the twin tunnels during dynamic loading

3.3 Parametric study on the behaviour of twin underground tunnels

In real situations, the height of soil cover or water depth need not be uniform. To understand the effect of these variations, different cases are studied. The effect of free water depth and the thickness of soil cover on the seismic behaviour of tunnels is studied. In addition to this, the effect of spacing between the tunnels in the lateral direction as well as in the vertical direction is also analysed.

Figures 6 and 7 represent the models for different overburden cases. It can be seen that the depth of soil cover and the depth of water above the tunnels are different. In twin tunnel model with varying overburden, the spacing between the tunnels is maintained as 4 times the diameter of the tunnel. The stresses around the tunnels are calculated by considering the varying depth of the soil as well as water.

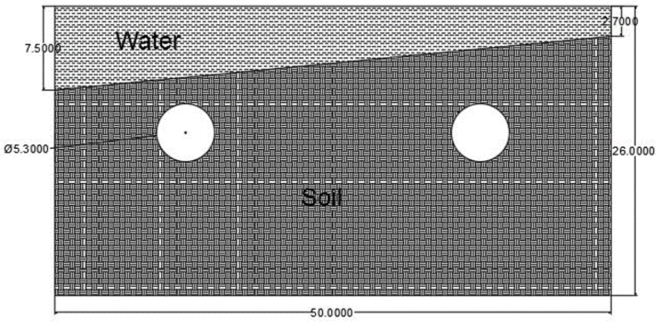

Figure 6 Twin tunnels subjected to varying overburden

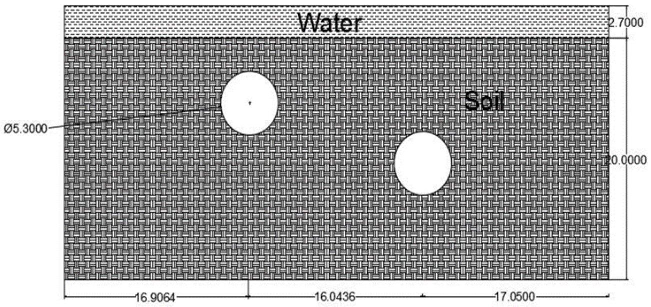

Figure 7 Twin tunnels located at different vertical depths

4. RESULTS AND DISCUSSION

The results of the static and dynamic analyses of twin tunnels with constant and varying overburden are shown in Figures 8 and 9. The maximum stress values in the twin tunnel model with varied overburden increased by about 7.3% when compared with tunnels subjected to uniform overburden. Deformation in copper twin tunnel model with varied overburden tunnel is 19.6% less than that of concrete twin model with uniform overburden. The dynamic response was studied for three different materials and the maximum stress values were seen in copper twin tunnels. When compared the behaviour between concrete and steel, stresses developed in tunnels made of concrete is found to be marginally less compared to steel when uniform overburden is considered.

The influence of lateral spacing between the tunnels was studied by applying earthquake load. Figure 10 shows the variation of stress when the spacing between the tunnels is 2d and 4d. There is an increase in stress by 4.2% for the copper twin tunnel model with 2d spacing in comparison with the twin tunnel model with 4d spacing.

When the tunnels are located at two different depth levels from the uniform soil bed, it was observed that the increase in stress was around 40.89% for the copper twin tunnel model as shown in Figure 11. The stress increase was found to be in the range of 40% for the tunnels with 2d spacing compared to 4d spacing.

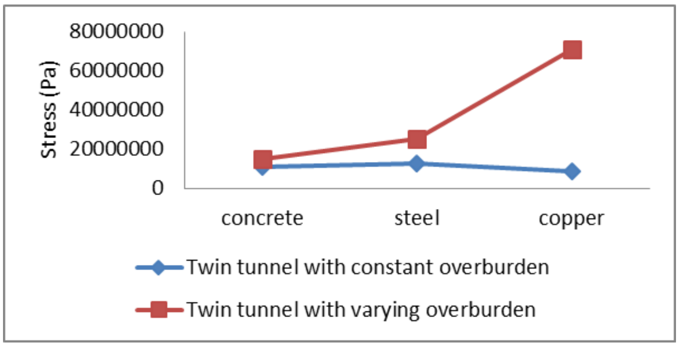

Figure 8 Stress in twin tunnel with constant and varying overburden: Static analysis

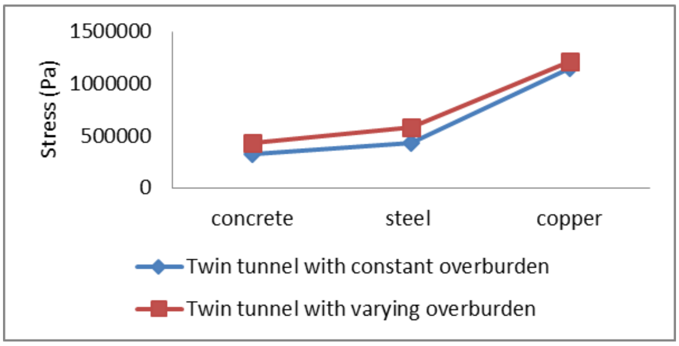

Figure 9 Stress in twin tunnel with constant and varying overburden: Dynamic analysis

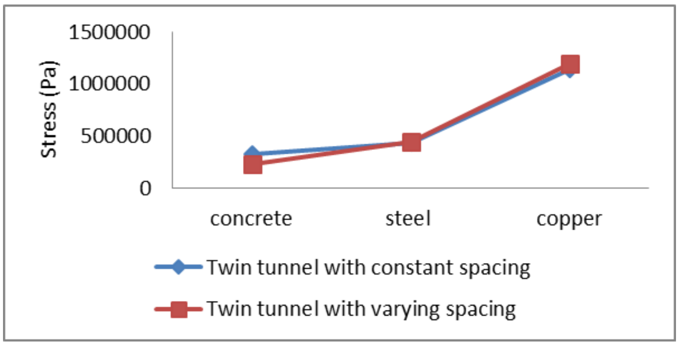

Figure 10 Stress in twin tunnels with 2d and 4d spacing: Dynamic analysis

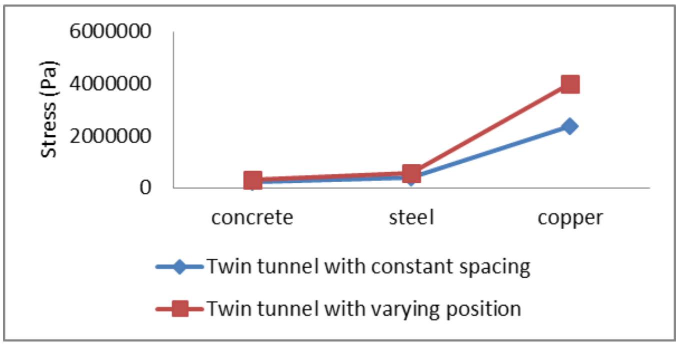

Figure 11. Stress in twin tunnels when located at same depth from uniform soil bed and at different depths: Dynamic analysis

5. CONCLUSION

In this study, the behaviour of single and twin tunnels buried below the water bed is analysed under static and dynamic loading conditions. Parametric studies involving the effect of varying overburden, spacing in lateral direction and depth of tunnels on the seismic response of twin tunnel models are carried out. Twin tunnels with varying overburden indicated that the maximum stresses developed was more for the varying overburden situation when compared with uniform overburden and can be quantified to an increase of 88% for the case considered. The results of dynamic analysis indicate that the twin tunnels located in varying overburden terrain showed an increase of 7.3% in the stress values when compared with the tunnels located below uniform overburden. When the tunnel models are subjected to dynamic loading with 2D and 4D spacing, concrete showed significant increase in stresses compared to the other two models.

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