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Research Article

THE EFFECT OF SOIL HEIGHT ON SEISMIC BEDROCK TUNNELS AND SOIL INTERACTION

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ABSTRACT
Method of Tunnel Building has significant effect on the response of seismic waves, because during excavation, the soil remains intact, and on the other hand, these types of tunnels are constructed where the depth of the tunnel is high. But on the surface tunnels, such as subway tunnels, often the method of excavation and lining should be used.
Faulting is one of the factors which damage the underground structures, especially linear underground structures during earthquake occurrence. Study of risk of faulting in the direction of a tunnel or other underground structures is very important.
In fact, many of underground structures and especially tunnels have intersection of faults. This makes them vulnerable to the effects of the fault motion. Therefore, when examining the sites for construction of underground structures, the faults should be considered and evaluated, in order to find the faults location and prevent and reduce any damages caused by faulting.
For this purpose not only the location of active faults should be identified exactly, but type of faults and how to move, how to move the past faults, how to choose the appropriate event or the impact of faults in the design and use of underground structures also should be reviewed.

***Keywords**: Seismic Bedrock Tunnels*

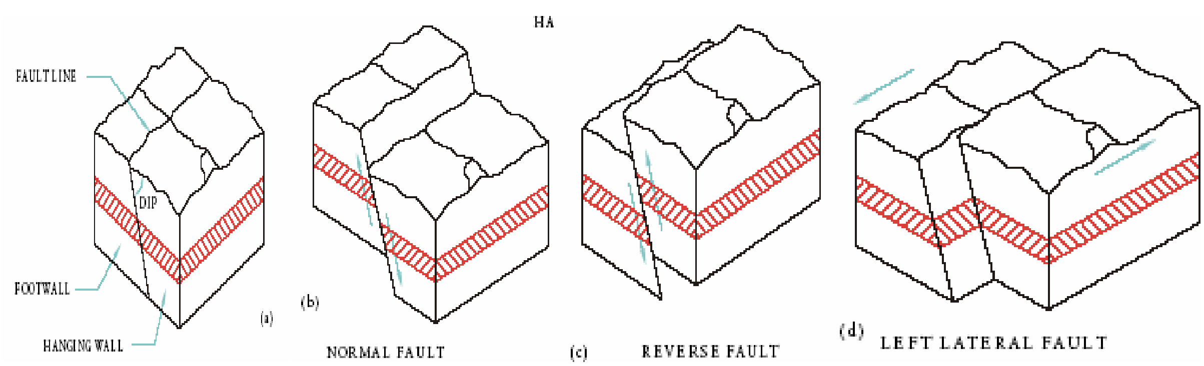
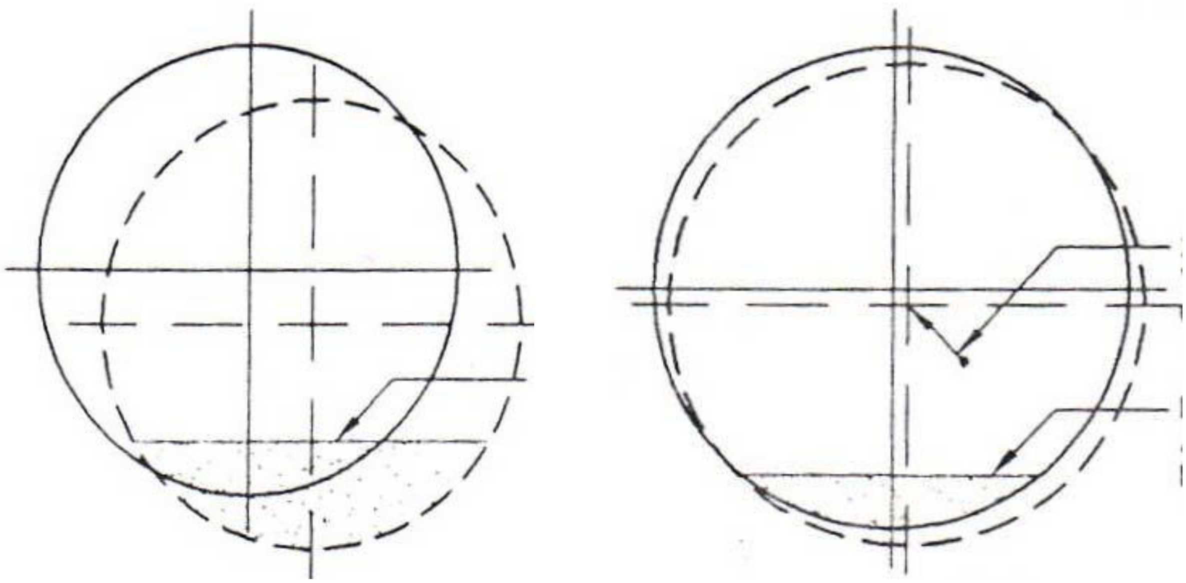


Figure 1: Different parts of a fault displacement

The effect of faulting on the design-usage must be carefully specified. For example, in railway tunnels, displacement is very sensitive, because lets them off the rails or impaired due to the displacement of the fault system there and it would bring disaster. In contrast, in water-transfer tunnels even if there occurred a significant displacement, but it couldn't cause any risks and water-transfer system could be continued with a little difference in flowage.
Usually design of tunnels or other underground structures so that they can resist against the fault couldn't be cost-effective; it is attempted to determine the exact location of faults through geological and geophysical methods and then to prevent the conjunction of tunnels and faults. It is a difficult process particularly in active tectonic zones where the linear structures have been constructed such as tunnels at least with hundreds meters length.
If it is impossible to be kept away the fault, usually through some displacement at the tunnel section, the tunnel should be connected to the fault in order to minimize damages; and reconstruction of the project should be planed.

For this purpose you can use the tunnel intentional weaknesses (such as construction joints, etc.) and concentrate the damages in certain areas. Increase of cross-section at the conjunction of tunnel and fault is another way to reduce the damages caused by faulting in the tunnels. As a result, in conjunction of tunnel and fault, the cross-section and displacement caused by the faulting should be larger and the extra section should be filled by pebble. If faulting occurs the cross- section area is equal to the desired cross-section.



Section of the tunnel before earthquake **Section of the tunnel after earthquake**

Figure 2: design of Los Angeles subway tunnel in conjunction of Hollywood Fault

Vulnerability of underground structures against earthquakes is because of disruption of the ground during an earthquake and the vibrations of earthquakes. Disruption of the ground during an earthquake consists of faulting, landslide and liquefaction.
Landslides are usually stimulated by earthquakes, especially in the input-output of tunnels can cause a lot of damages to underground spaces. Many reports of damages to underground spaces in earthquakes proved that landslides in the tunnel entrances caused above damages.
If underground space is constructed in loose sediments particularly with a high percentage of sand and silt, liquefaction might be cause of any damages to underground spaces. These damages have been seen on the subway tunnels in urban areas which crossing the sediment discharge.
Damage caused by disruption (such as faulting or landslide) can occur in certain areas that could be explored and prevented through the detailed studies of engineering geology. But vibration can be caused by any fault motion at a far or close distance to the underground space and its intensity can be highly variable.
There are different types of seismic waves; each wave has its own effect on underground structures.
The response of underground spaces for the vibrations caused by the earthquake can be categorized in three deformation groups: axial deformations, curved deformations and hoop deformations.
Usually in order to design the underground structures it is required that the system is designed with flexibility and ductility potentials provided that its static stability is not endangered. It is also necessary to consider some issues such as the possibility of intensification and effects of structure interaction with environment. These factors can lead to increase seismic motions.
The soil-structure interaction in the underground structures has important effects, but if the structure is designed to follow the ground movement system, the effect of interaction is reduced to minimum. Another important factor for underground spaces behavior against vibrations is angle of conjunction of waves and tunnel wall.

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Seismic waves can conjunct to the linear structures such as tunnels with different angles and whatever (by reducing the angle of conjunction of waves and tunnel) length of tunnel is more impressed, the ground displacement amplitude would be reduced.

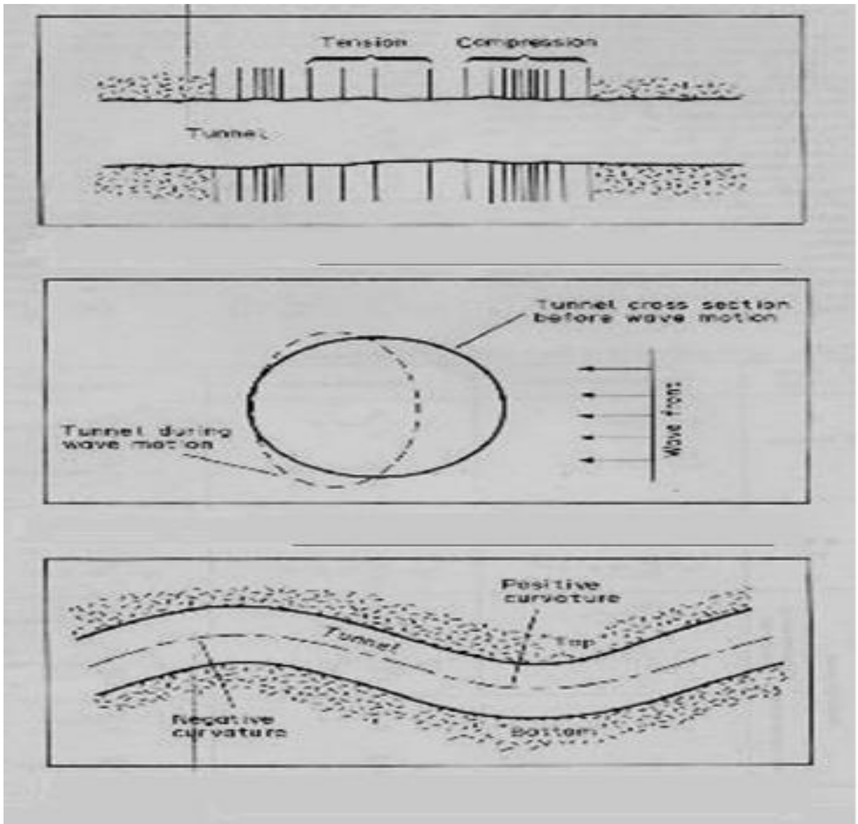

Figure 3: Effect of waves and types of deformation caused by ground vibration during an earthquake

Angle of conjunction of wave and tunnel has a significant effect on the values of curvature and bending of tunnel, resulting in deformation of tunnel during an earthquake.

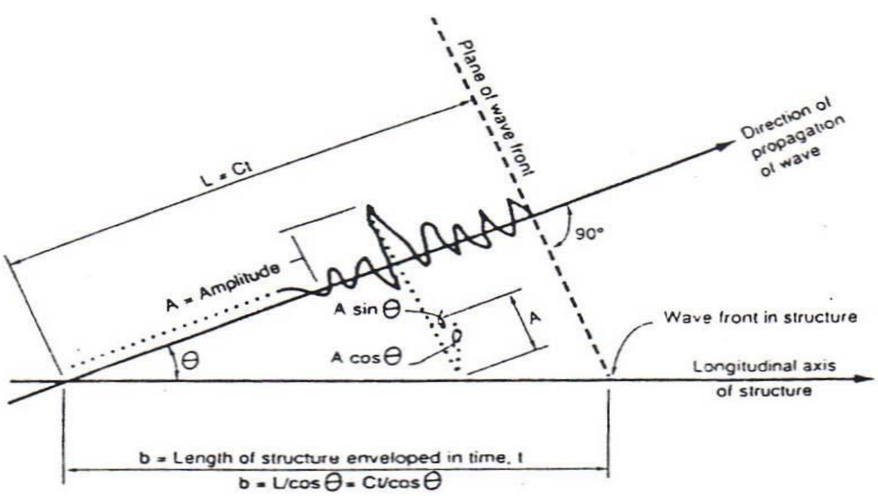

Figure 4: Effect of angle of conjunction of wave and a linear structure such as tunnel and related parameters

Seismic waves may be intensified or damped when they move through the bedrock depending on the type and thickness of the bedrock. Therefore, one of the most important parameters for seismic response of tunnels is the height of soil over bedrock up to under the bed of tunnel. In order to study this parameter and its effect on seismic interaction of tunnel and soil, several types of sandy and clay soil at different depths of the rock; and a real earthquake with high frequency has been used.
Choose of an appropriate model for soil is the most important challenge to analyze the interaction of soil and tunnel. Finite elements have been used for soil-tunnel model.
All soil-tunnel models have been analyzed under earthquake with high frequency (HAV).

Table 2: Properties of earthquakes with high frequency

Type of earthquake	Properties of earthquake	Recorded zone	Date of earthquake	Magnitude of earthquake	Max. acceleration (g)	Max. velocity (m/s)	Ratio of a/v
Hav	a/v > 1.2	Lytle Greek	Sep.12 1970	5.4	0.198	0.096	2.03

To have a dynamic analysis of soil-tunnel models, three models with dimensions of 500 x 40 m and 800 x 100 m (tunnel with distance from the bedrock) and 500 x 21 (tunnel close to bedrock) have been used. So that the thickness of soil from the bedrock in model 500 x 40 m is 20 m, in model 800 x 100 is 80 m and in model 21 x500 m is 1 m.
Optimal width is 500 m for the soil models with depth of 40 and 21m, and optimal width is 800m for the soil models with depth of 100m. The tunnel used in this study has an external diameter of 10 m and primer thickness of 0.5m. All models had soil-tunnel with 10m thickness; and soil behavior in all models was assumed to be elastic. The concrete behavior has been assumed elastic with compressive strength of 28MPa and density of 2400Kg/m3. To consider the effect of possible overloads on the soil surface, a uniform linear load of 14715 (N/M) with length of 40m has been located on the center of models. The type of elements used in the soil models are two-dimensional, plane strain, three- and four-nodes and continuous.

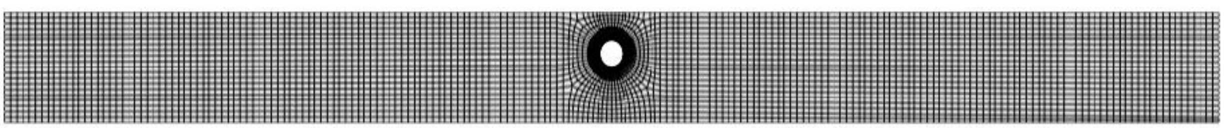

Figure 5: The finite element model of tunnel at a distance of 20 m of bedrock

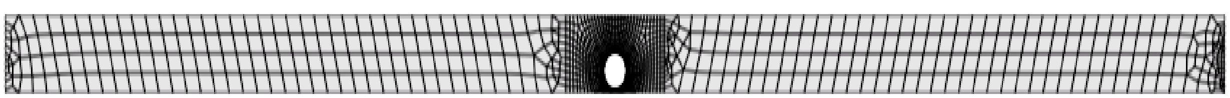

Figure 6: The finite element model of tunnel at a distance of 1 m of bedrock

In regards to soil existing around the underground structures such as tunnels, since its outer layer is in contact with the soil (the interface of soil and tunnel) and also due to the dynamic nature of the analysis, the friction between soil and tunnel has been calculated by software.
Seismic response of soil-tunnel system during earthquake should be affected by the interaction of two interrelated systems, e.g. tunnels and soil. In this study, all soil-tunnel models were analyzed dynamically and max. acceleration has been drawn toward the depth on the central line of model, from bedrock to surface of soil; in order to determine max. response acceleration in the soil.
The results of these studies indicate that the rate of acceleration in tunnel is much higher than in other parts of the earth. This is because of tunnel in a soiled-environment and interaction of soil and tunnel. Max. response acceleration in the tunnel and also in all soils under earthquake (HAV) in model 800 x 100 is higher than model 40 x 500.

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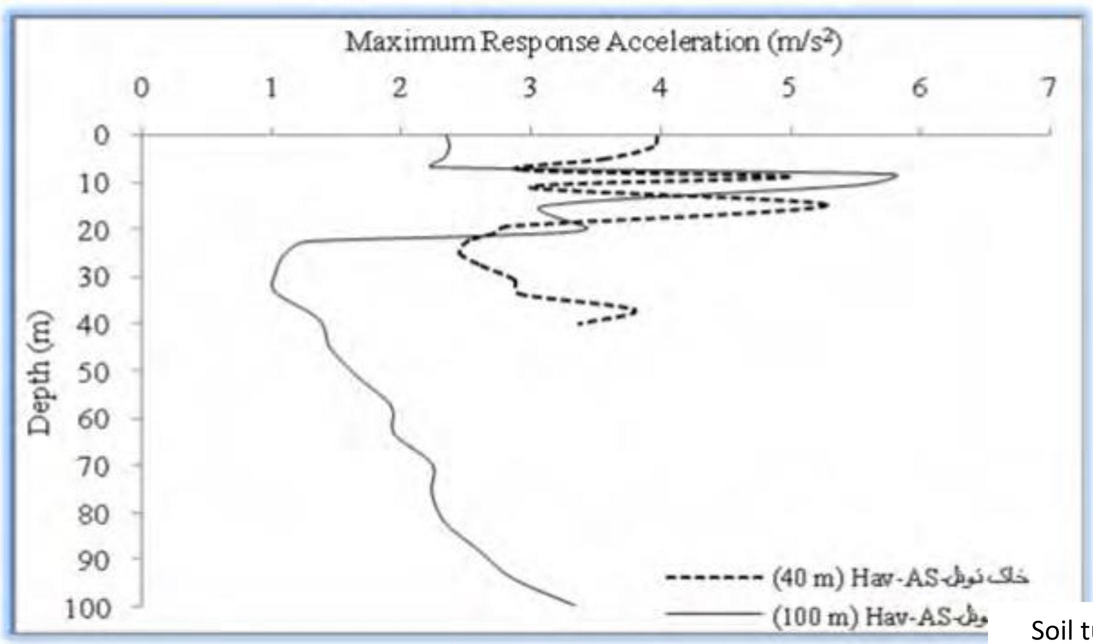
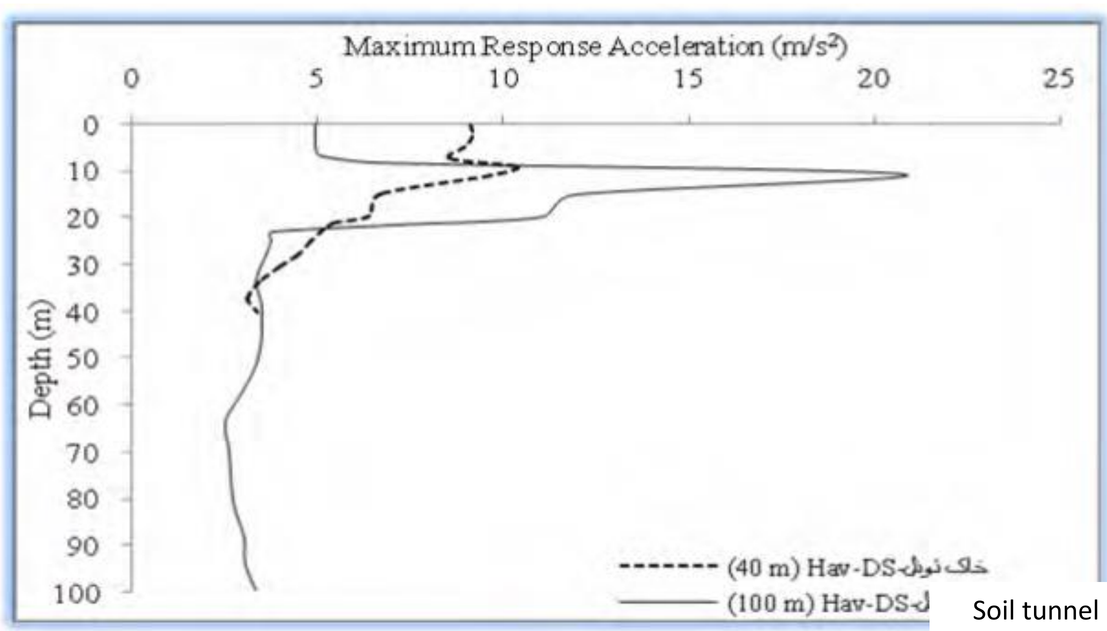
In fact, if thickness of soil over bedrock is increased, response acceleration will be increased; so whatever the period of soil and earthquake are close to each other response acceleration will be higher.



Soil tunnel
Soil tunnel

Figure 7: Effect of soil thickness of bedrock on the acceleration for models with 4 depth and the optimal length of 500m and 800m



Soil tunnel
Soil tunnel

Figure 8: Effect of soil thickness of bedrock on the acceleration for models w)m depth and the optimal length of 500m and 800m

To study the effect of soil thickness of bedrock on response of stresses and strains in the tunnel (maximum principal stresses on plane σ_1 & σ_3) and the maximum shear stress (τ_{max}) and maximum principal strain on plane ε_3 and maximum shear strain (γ_{max}), the tunnel in two different situations:

a) Put tunnel into the soil away from bedrock, so that thickness of soil in model of 40 m is 20 m and in model 100 m is 80 m.
b) Once put tunnel near bedrock, so that thickness of soil is only 1m.
By division of stress and strain in mode (a) into stress and strain in mode (b) the response factor of stress was calculated as $S\sigma 3$, $S\sigma$, $S\ \tau_{max}$; and response factor of strain was $S\varepsilon$ and $S\ \gamma_{max}$.
Maximum surface accelerations, the depth of placement, structural constraints in limited certain layers of soils, as well as the flexibility of covering of tunnel relative to environmental damping; and flexibility of covering of tunnel in the analysis of cross- and longitudinal-section of tunnel, are known as the most important factors affecting on the seismic behavior of underground structures.
By dynamic analysis of tunnel in a cross-section by the use of finite element methods, the location and internal forces have been investigated in covering of tunnel. Effect of earthquake for shallow tunnels was higher than deep tunnels relative to the surface.
The studies that examine the effect of lateral structures on seismic behavior of tunnels have shown that one of the factors affecting on interaction between tunnel and adjacent building depended on the depth of the tunnel (height of soils on bedrock).
Here, only the subjects related to our study are rendered. In order to study of this parameter with regard to the mentioned model and through changing the location of tunnel in height of soil-layer; some analyses with first three frequency have been carried out. In other words, only the depth of tunnel from the surface was investigated.
Studies show that tunnels have no effects on the natural frequencies.
The most important seismic parameters which destruct the tunnels, max. acceleration of ground higher than 0.5g and durability of vibrations could be mentioned because they cause fatigue and large deformation around the tunnel. Other factors contributing to destruction of earthquake is intensity of earthquake. Unlike the earthquake magnitude, intensity of earthquake can be considered as a criterion to determine damages because it is developed based on rate of earthquake damages. The studies show that rate of earthquake damages will be decreased if distance from the fault is increased; and if maximum acceleration at the surface is increased, the damages of tunnel will be increased. The maximum acceleration of 0.5g causes maximum damages. The studies show that in more depth tunnels we could see less damage. Under the same situations, a tunnel at a depth of 50 m was damaged about 40% less.
Choosing a proper model for the soil is most important problem in order to analyze the interaction of soil and tunnel. The soil-tunnel model of finite elements is used here.
In this regard, the soils have been divided into four categories: AS soils found in the first and second grounds; DS Soils found in the second and third grounds; OC and NC Soils found in the first and second grounds. All types of soil at depths of 40m and 100m on the ground have been studied. In fact, research of studies have shown that if thickness of soil over bedrock is increased, response of acceleration will be increased and whatever the period of soil and earthquakes are much closer to each other, the rate of response will be more intensified.

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