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INNOVATIVE METHODS FOR THE DESIGN OF GEOTECHNICAL SYSTEMS

Research Unit 2

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UNDERGROUND STRUCTURES
ROCK TUNNELS AND CAVERNS

1. Introduction

It is the purpose of the present report to summarise the results of the research studies carried out during the first year by the Research Units (RU's) of Politecnico di Torino, Department of Structural and Geotechnical Engineering (Polito 1), Politecnico di Milano, Department of Structural Engineering (Polimi 1), and Eucentre, Pavia (Eucentre), coordinated by Giovanni Barla (Polito 1). According to the 1st year programme of activities, the main topics of the work carried out so far are as follows:

- State of the art of underground structures subject to earthquake damage
- Definition of seismic input
- Design analyses of underground structures
- Monitoring of underground structures.

2. State of the art of underground structures subject to earthquake damage

One of the main activities carried out is the collection of information about the damage conditions suffered by tunnels and underground cavities in rock at depth due to earthquakes. A summary of the work performed so far is reported in a paper by Corigliano et al. (2006), which was presented at the recent First European Conference on Earthquake Engineering and Seismology, Geneva, 3-8 September 2006 (see Enclosure 1). A collection of descriptive forms which are intended to report the different case histories investigated is being prepared (see Enclosure 2 for a typical case: Bolu Tunnel, Turkey).

Underground facilities are usually less vulnerable to earthquakes compared with above-ground structures, however several tunnels worldwide have been heavily damaged by ground shaking. Dowding and Rozen (1978) grouped damages due to earthquakes in underground structures into three main categories:

(1) damage from ground shaking;
(2) damage from fault dislocation;
(3) damage by earthquake-induced ground failures (e.g. liquefaction and landslides).

The main focus of this report is on damage caused in deep tunnels by ground shaking. Tunnels with large overburden stress are usually bored in rock and thus the effects of ground instabilities like liquefaction or landslides are immaterial. Even though fault dislocations are one of the most important causes of tunnel collapse, they are only indirectly associated with seismic loading and the caused damage is concentrated in a relatively small area that can be identified by geological and seismic tectonic studies.

The major factors influencing the seismic response of an underground structure include (Dowding and Rozen, 1978; St.John and Zahrah, 1987):

- shape, size and depth of the structure;
- mechanical properties of the surrounding soil or rock;
- mechanical properties of the structure;
- severity of ground shaking.

Usually, earthquake-related damage in underground structures is mainly concentrated in zones where there is a sharp variation of mechanical or geometrical properties in both the ground and/or in the structure.

The level of shaking generally increases as the stiffness of the ground decreases. Tunnels at low depth in soft soils are seismically more vulnerable than underground structures bored in rock and with large overburden stress. However, occasionally also deep tunnels have been damaged by earthquakes due to either the effects of strong earthquake intensity or the presence of weak zones within the rock mass. Usually tunnels that experience co-seismic damage due to the presence of weak zones have shown problems also during the construction phase. On the contrary, co-seismic damage due to strong ground shaking may be found in tunnels located close to an active fault.

Dowding and Rozen (1978) identified three levels of damage for underground excavations in rock due to ground shaking:

- "no damage", which implies that post earthquake investigations revealed the absence of new cracking or falling rock blocks;
- "minor damage", which implies the fall of rock blocks and formation of new cracks;
- "damage", which implies major fall of rock blocks, severe formation of cracking and closure of the opening.

These authors also proposed a correlation between tunnel damage and peak ground acceleration (PGA) calculated at the free surface immediately above the tunnel through an attenuation law. They suggest that "minor damage" is expected when the value of PGA ranges between 0.19 g and 0.50 g. The corresponding thresholds for peak particle velocity (PGV) range approximately between 20 cm/s and 90 cm/s. The reliability of this correlation depends upon two strictly related aspects of the problem. The first is that peak ground motion parameters are evaluated at the free surface because in-depth measurements of ground motion are usually unavailable. The second is that these parameters are often estimated using attenuation laws which carry a certain level of uncertainty.

The values of PGV suggested by Dowding and Rozen (1978) are typical for near-fault earthquakes and for such events the predictions of PGV made by attenuation relations are even more inaccurate. In relative terms one of the most dependable of such relations is that developed by Bray and Rodriguez-Marek (2004). This relation has been used to correlate the ground motion parameter PGV to the damage thresholds defined by Dowding and Rozen (1978) (see Enclosure 1). For lined tunnels earthquake-related damages may include spalling, cracking, crushing, falling of the concrete lining, bending of reinforcing bars, rising of the invert, rock falling and failure of the tunnel liner. For unlined tunnels in rock, damages may include rock fall, spalling, local opening of joints and obstructing of the opening.

2. Definition of seismic input

A careful review of the documents collected so far shows that most earthquake-related damaged tunnels worldwide were located in the vicinity of the causative fault. The characteristic of ground motion in the vicinity (i.e. <10-15 km) of a causative fault can be significantly different from that of the far-field. Near-field ground motion is strongly influenced by the rupture mechanism, the direction of rupture propagation relative to the site, and possible permanent ground displacements resulting from the fault slip (Stewart et al., 2001). These latter two factors are usually identified respectively as "rupture-directivity" and "fling step" effects.

Recent earthquakes such as the 1994 Northridge (California), the 1995 Kobe (Japan), the 1999 Kocaeli (Turkey), and the 1999 Chi-Chi (Taiwan) earthquakes, demonstrated the high damage potential of near-field ground motion. In light of this, the study of the dynamic behaviour of underground structures located in the vicinity of seismically active faults requires a careful selection of input time histories. The near-fault zone is usually assumed to be within an epicentral distance of about 20÷60 km from the rupture (Stewart et al., 2001), however only at distances smaller than 10÷15 km a major damage to underground facilities is expected to occur.

For a strike-slip focal mechanism the directivity pulse is oriented along the strike-normal direction whereas the static ground displacement is aligned along the strike-parallel component. On the contrary, for a dip-slip source mechanism the directivity pulse is oriented along a direction normal to the fault dip and has components in both the vertical and the horizontal strike normal directions. The static ground displacement is aligned in this case along the direction parallel to the fault dip and has components in both the vertical and the horizontal strike normal directions (Somerville, 2002).

2.1 Rupture directivity effects

The term "directivity" refers to the direction of rupture propagation as opposed to the direction of ground displacement. In the aftermath of an earthquake a site may be classified as affected by forward, backward or neutral directivity effects.

Forward-directivity effects occur when the following two conditions are met:

1) the rupture front propagates toward the site,
2) the direction of slip on the fault (rake) is aligned with the site.

The effects of forward-directivity are generated because the velocity of fault rupture is only slightly less than the speed of propagation of shear (transversal) waves in the surrounding rock mass. As the rupture front propagates from the hypocenter, a shear wave front is generated by the accumulation of the shear waves travelling ahead of the rupture front (Somerville et al., 1997). Forward-directivity effects yield a ground motion dominated by a velocity pulse characterized by large amplitudes and short durations (pulse-like motion). These effects are typically long period signals and are best observed as velocity or displacement time histories (Bray and Rodriguez-Marek, 2004). Conversely neutral or backward-directivity effects produce long duration motion of relatively low amplitude.

2.2 Fling step effects

The "fling step" is the static component of the near-fault ground motion and is characterized by a ramp-like step in the displacement time-history and a one-sided pulse in the velocigram. Several authors including Kostadinov and Yamazaki (2001), Faccioli et al. (2004) and Graves (2004) have proposed analytical formulations to model the fling-step effect. They differ for the mathematical functions used to approximate the velocity pulse (e.g. trigonometric, triangular, Gaussian etc.). Every model is described by two parameters: the final fault offset and the duration of the velocity pulse. Furthermore, Kostadinov and Yamazaki (2001) proposed a procedure to remove the static displacement in near-field seismic records in order to estimate the static component of peak ground velocity (PGV). Fling-step effects are independent from epicentre location and they decay rapidly with the distance "d " from the fault (i.e. they attenuate proportionally to $1/d^2$). Furthermore these effects are important only for surface ruptures say less than about 5 km from the fault trace (Graves, 2004).

2.3 Ground motion simulation

For many types of above-ground structures, the seismic action is often represented in the form of either an acceleration or a displacement response spectrum. For underground structures instead, a correct simulation of the response requires the execution of a complete dynamic time-history analysis. To obtain the acceleration time histories many options are available including artificial spectrum-compatible accelerograms, synthetic records generated by a seismological model of the source and real accelerograms (i.e. time histories recorded in real earthquakes). However, for underground structures located in the vicinity of a fault rupture, the ground motion should also reflect the features described above namely directivity effects and fling step. The use of real accelerograms is preferred, however it is influenced by two problems. First the lack of ground motion recordings below the ground surface and, second, the difficulty to adequately scale the time-histories recorded at the free surface. Even though the advent of digital accelerographs has increased the number of near-fault accelerograms, often the use of synthetic records and ground motion simulation is still required given the scarcity of actual recordings.

In the present research project the near-fault time-histories required for studying the seismic response of rock tunnels have been obtained from synthetic records generated using the approach proposed by Hisada and Bielak (2003) which is based on the application to a stratified medium of the method of generalized reflection and transmission coefficients using an extended kinematic source. The method explicitly considers the static offset due to surface faulting and allows one to investigate the effects of fling step and rupture directivity on the computed near-fault ground motions.

3. Design analyses of underground structures

Assessing the seismic response of an underground structure is a problem significantly different from that of a corresponding above-ground facility since the overall mass of the structure is usually small compared with the mass of the surrounding soil and the overall confinement acts as a strong damper of the seismic excitation. Therefore the seismic response of an underground structure is mainly controlled by the response of the surrounding ground and by the imposed ground deformation. The seismic response of underground structures may be assessed using two approaches (Hashash et al., 2001):

- free-field deformation approach;
- soil-structure interaction approach.

The two categories include various sub-methods characterized by different levels of approximation depending on design stage, knowledge of geologic setting, and geotechnical parameters. Concerning the types of analyses they may be grouped into three categories:

- pseudo-static;
- simplified dynamic;
- detailed dynamic analysis.

For engineering purposes underground structures may be assumed to undergo three primary modes of deformation during seismic shaking (Owen and Scholl, 1981):

- compression/extension;
- longitudinal bending;
- ovaling.

Only in detailed dynamic analyses the coupling between the response in the longitudinal direction (i.e. along the tunnel axis) and the one along the tunnel cross-section (i.e. along the transversal direction) is considered. In the following subsections the most important aspects related to the seismic response of underground structures as proposed within the present research project are briefly summarized. Also, a simplified approach in studying the seismic response of rock tunnels which takes into account the interaction of the underground structure with the surrounding ground and at the same time adequately considers the features of near-fault ground motion is proposed as developed during the first year of activities. Different analyses have been used for studying the transversal and longitudinal response. For the former the developed approach is typically pseudo-static whereas for the latter it is a simplified dynamic approach.

3.1 Analysis of transversal response (ovaling deformation)

The seismic response of an underground structure is controlled by the response of the surrounding ground and by the imposed deformation. In this regard, the most critical deformation pattern induced by ground shaking to a tunnel lining is the ovaling of the cross-section. The transversal behaviour is usually studied by analyzing the response of the cross-section to an imposed uniform strain field using the pseudo-static approach (Penzien, 2000). This is done for two reasons. Firstly, because the dimensions of a typical lining cross-section are small compared with the wavelengths of dominant ground motion producing the ovaling. Secondly, because the inertia effects in both the lining and the surrounding ground as produced by dynamic soil-structure interaction effects are relatively small (Penzien, 2000).

The analysis of the transversal response is performed by considering a lined circular tunnel in plane strain conditions. The earthquake loading is modelled as a uniform, quasi-static strain field simulating a pure shear deformation. The relations for displacements, bending moment, thrust and shear forces are derived following the same approach as used by Einstein and Schwartz (1979), in which however the assumption that the induced internal forces are caused by excavation has been removed and replaced with an imposed, external quasi-static loading distribution. The solution has been derived for two contact conditions at the structure-rock interface: full-slip and no-slip as described in detail in Enclosure 1. The true contact conditions at the ground-structure interface are unknown and the full and no-slip conditions simply represent the two extreme cases in which the real situation is bounded. The full-slip contact condition is usually adopted to obtain the extreme values of the bending moment and shear in the tunnel lining whereas the no-slip assumption is used to find the maximum values of the thrust acting on the lining (Wang, 1993).

A key parameter for definition of the state of stress in the tunnel lining is the maximum shear strain evaluated in free-field conditions. For shallow tunnels the shear strain profile can be easily obtained by considering a horizontally layered system and using one-dimensional wave propagation theory (Wang, 1993). In near-fault conditions the assumptions of the previous approach are no longer valid (i.e. one-dimensional wave propagation theory with the wave front impinging in the vertical direction). To compute the earthquake-induced shear strain field in the vicinity of a causative fault, the displacement time histories at four points around the cross section of the tunnel were calculated using the Hisada and Bielak (2003) approach.

3.2 Analysis of longitudinal response (axial and bending deformation)

To study the tunnel response along the longitudinal direction (which involves axial and bending deformations) a finite element stick model has been purposely developed by subdividing the tunnel into a finite number of frame elements with lumped mass, connected to the surrounding ground by a series of *frequency-dependent springs and dashpots in parallel (i.e. a Kelvin-Voigt model), representing the effects of ground deformability and energy dissipation (though Sommerfield radiation and material damping) . Wave scattering or kinematic interaction is not accounted for and thus this model can be ascribed to the class of simplified dynamic methods to analyse underground structures. The seismic excitation is inputted at the external nodes of the Kelvin-Voigt model through appropriate three-component free-field displacement and velocity time-histories. The synthetic records are generated using the Hisada and Bielak (2003), which allows to properly model not only the spatial variability and phase shift of ground motion but also the typical features of near fault ground motion (i.e. directivity and flying step effects). Also this model has been described in Enclosure 1.*

3.3 Case studies

The simplified approach as developed so far, which allows one to consider both the transversal and longitudinal response of deep tunnels subject to earthquake loading need be validated. This is being done by taking typical case studies for which reliable input data are available and by comparing the results obtained by the simplified approach with the results derived by more advanced numerical analyses.

Several analyses involving the coupled effect of seismic source, propagation path, complex geological features and dynamic soil-structure interaction, are being been carried out by using a high-performance spectral element computer code, implemented in parallel architectures. The capabilities of this computer code are enhanced by the implementation of the so-called Domain Reduction Method (DRM), the main feature of which is to provide the exact coupling of the wave propagation solutions in different domains, so that the wave propagation from the seismic source, and the dynamic response of the tunnel can be effectively studied by two numerical models in series, with a significant saving in computer time.

At present, the seismic response of a rock tunnel located in Southern Italy, along the railway line connecting Caserta to Foggia is being considered (see Enclosure 3). As well known, the northern sector of southern Apennines, the Sannio region, is among the most active seismic regions in Italy as it was struck by four large destructive earthquakes in the last three centuries, the latest in 1805. The seismic analyses of the tunnel are carried out by simulating the reactivation of a fault located in close proximity to the tunnel. As a final step, the results obtained from advanced numerical analyses are compared with those determined with simplified methods: The aim is to assess the potentials of simplified methods in the design analysis of deep tunnels in rock with a close view paid to engineering applications and design needs.

4. Monitoring of underground structures

Infrastructure systems are the most critical part of the asset of a nation: anomalies or collapse can produce loss of human lives and negative consequences on the inner global product (Aktan et al. 1998). In many areas the ageing and maintenance of civil infrastructures introduce new problems for the asset management, whose solution requires technical, scientific and managerial abilities (Aktan et al. 2000). These aspects caused in the last decades an increasing interest on the subject of structural health monitoring (SHM) from researchers belonging to different areas, not only engineering, but also physics, economics and biology.

SHM encloses the measurement operations of the environmental conditions, the external loads and the structural response for the identification of anomalies or damage which can cut down the serviceability or the safety of a structure (Aktan et al. 2000). A big amount of publications about SHM of bridges and buildings is now available, while the efforts made in developing monitoring systems for underground structures are far to be sufficient: these constructions, in fact, have been considered for a long time to be insensitive to extreme events such as earthquakes and hurricanes. Nevertheless, considering the complexity and the high costs related to underground structures, an efficient monitoring system must be regarded as a fundamental tool of control and mitigation of risks, both during the construction activities and the service life (Bhalla et al. 2005).

In the most general terms, damage can be defined as changes introduced into a system that adversely affects its current or future performance (Sohn et al. 2003): the basic premise of most damage detection methods is that damage will alter the stiffness, mass, or energy dissipation properties of a system, which in turn alter the measured dynamic response of the system. Although the basis for damage detection appears intuitive, its actual application poses many significant technical challenges. The most fundamental challenge is the fact that damage is typically a local phenomenon and may not significantly influence the lower frequency global response of a structure that is normally measured during vibration tests. Moreover, environmental and operational variations, such as varying temperature, moisture, and loading conditions affecting the dynamic response of the structures can often mask subtler structural changes caused by damage.

The damage state of a system can be described as a five-step process, each one related to the following questions:

- is there damage in the system (existence)?
- where is the damage in the system (location)?
- what kind of damage is present (type) ?
- how severe is the damage (extent)?
- how much useful life remains (prognosis)?

Answers to these questions in the order presented represents increasing knowledge of the damage state: the statistical models are used to answer these questions in an unambiguous and quantifiable manner (Sohn et al. 2003, Van der Auweraer & Peeters 2003).

A state-of the art has been produced, focusing its attention especially on sensors and current procedures employed in the case of tunnels. In the first part the basics of structural damage detection have been outlined and the modern probabilistic approach has been briefly presented (Sohn et al. 2003). The second part of the work refers a state-of-the-art of sensors and technologies for structural monitoring, considering both static and dynamic measurements.

5. Enclosures

Enclosure 1: Corigliano M., Lai C., Barla G.: Seismic response of tunnels in near fault conditions. First European Conference on Earthquake Engineering and Sismology. Geneva, 3-8 September 2006, paper n. 998.

Enclosure 2: Example Form for Case Studies: Bolu Tunnel Case Study.

Enclosure 3: Corigliano M., Scandella L., Barla G., Lai C.G., Paolucci R.: Seismic analysis of underground structures: a case study in Southern Italy. Abstract submitted to the 4th International Conference n Earthquake Geotechnical Engineering, Thessaloniki, 2007.