Doctoral Dissertation

3-D Analytical Simulation of Ground Shock Wave Action on Cylindrical Underground Structures

by

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EXTENDED ABSTRACT

The use of buried pipeline and tunnel networks for the transportation and distribution of environmentally hazardous materials (waste, fuels, chemicals etc.) is booming in Greece over the last few years. The design of such structures against accidental actions, such as the ground shock originating from a strong earthquake or from a surface explosion in the vicinity of the structure (Figure 1), is of extreme importance: even easily repairable (for e.g. a road tunnel) tension or shear cracks of small width could result in leakage of hazardous materials, and provoke a severe ecological disaster (ACI Committee 224, 1995).

Two new analytical methodologies for the design of such cylindrical underground structures under ground shock are developed in the present Thesis, adapted to the high safety standards of networks transporting and distributing environmentally hazardous materials: the first regarding seismic waves and the second ground waves originating from surface explosions. The solutions presented here incorporate **3-D thin shell theory for the analytical calculation of strains in underground pipelines and tunnels,** when soil-structure interaction can be ignored. In this way, the proposed are essentially differentiating from existing methodologies, where strains due to ground shock are computed in the free-field and considered equal to the strains of a flexible buried structure (Newmark, 1968, Kuesel, 1969, Yeh, 1974, St. John and Zahrah, 1987, Dowding, 1985).

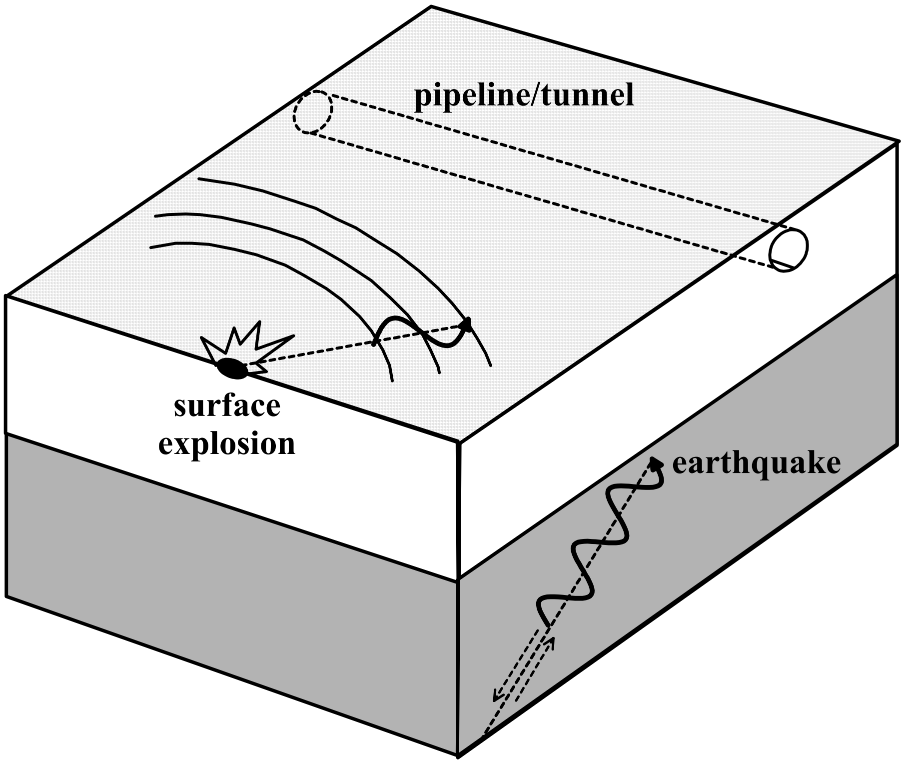

Figure 1. Propagation of ground shock waves provoked by an earthquake or a ground surface explosion.

Strain analysis by means of shell theory leads to the calculation not only of the maximum axial, shear and hoop strain on the structure, which is possible for all wave types by employing the state-of-the-art of existing methodologies, but also of their distribution along the cross-section of the structure. **The major advantage arising from this consideration is the ability to accurately superimpose the components of strain, so as to calculate the maximum tensile or compressive (major and minor principal) strain in the cross-section and, especially for steel structures, the von Mises strain.**

The methodology for calculating design strains due to the propagation of seismic S, P and Rayleigh waves with plane front is presented in the **first part** of the Thesis. **The solution developed herein considers not only pipelines and tunnels constructed in a homogeneous medium (i.e. rock) but also near the surface of a two-layer profile, consisting of a "soft" soil layer overlying the seismic bedrock, a rather common case that is overlooked in the existing bibliography.**

Strains in the underground structure are computed analytically by assuming that, when soil-structure interaction can be ignored, the dynamic displacement of the structure due to the propagation of the harmonic waves is equal to the displacement of the surrounding soil. The resulting, rather complex, relations are consequently maximized with respect to the unknown parameters of the problem, to conclude to simple design relations for different wave types and local soil conditions.

The procedure for computing the design strains can be broken into the following discrete steps, summarized in the flow chart of Figure 2 for 3 basic profiles (Figure 3), that cover all cases of flexible underground structures found in practice:

Case 1: Pipelines and tunnels constructed in rock, in depths larger than the influence zone of Rayleigh waves,

Case 2: Pipelines and tunnels constructed near the surface of rock or stiff soil formations, and

Case 3: Pipelines and tunnels constructed near the surface of soft soil formations, overlying the seismic bedrock.

Results of the proposed methodology are verified against the results of a series of 3-D dynamic FEM analyses, simulating S, P and Rayleigh wave propagation. Analytical solutions are also employed in the prediction of the actual behavior of pipelines and tunnels during the strong earthquakes of Kobe (1995), Chi-Chi (1999) and Düzce (1999), using a series of case studies sorted in a database which resulted from a thorough bibliographic research. This database includes 52 different sites where different types of damages have appeared in concrete tunnels and transportation pipelines, incorporating data for the local soil conditions, the strong motion in the vicinity of the structure and the form of the damage that appeared at each site. To aid the comparison, the database also includes 54 concrete tunnels and pipelines that stayed intact during the earthquake, although they were also constructed at the meizoseismal area.

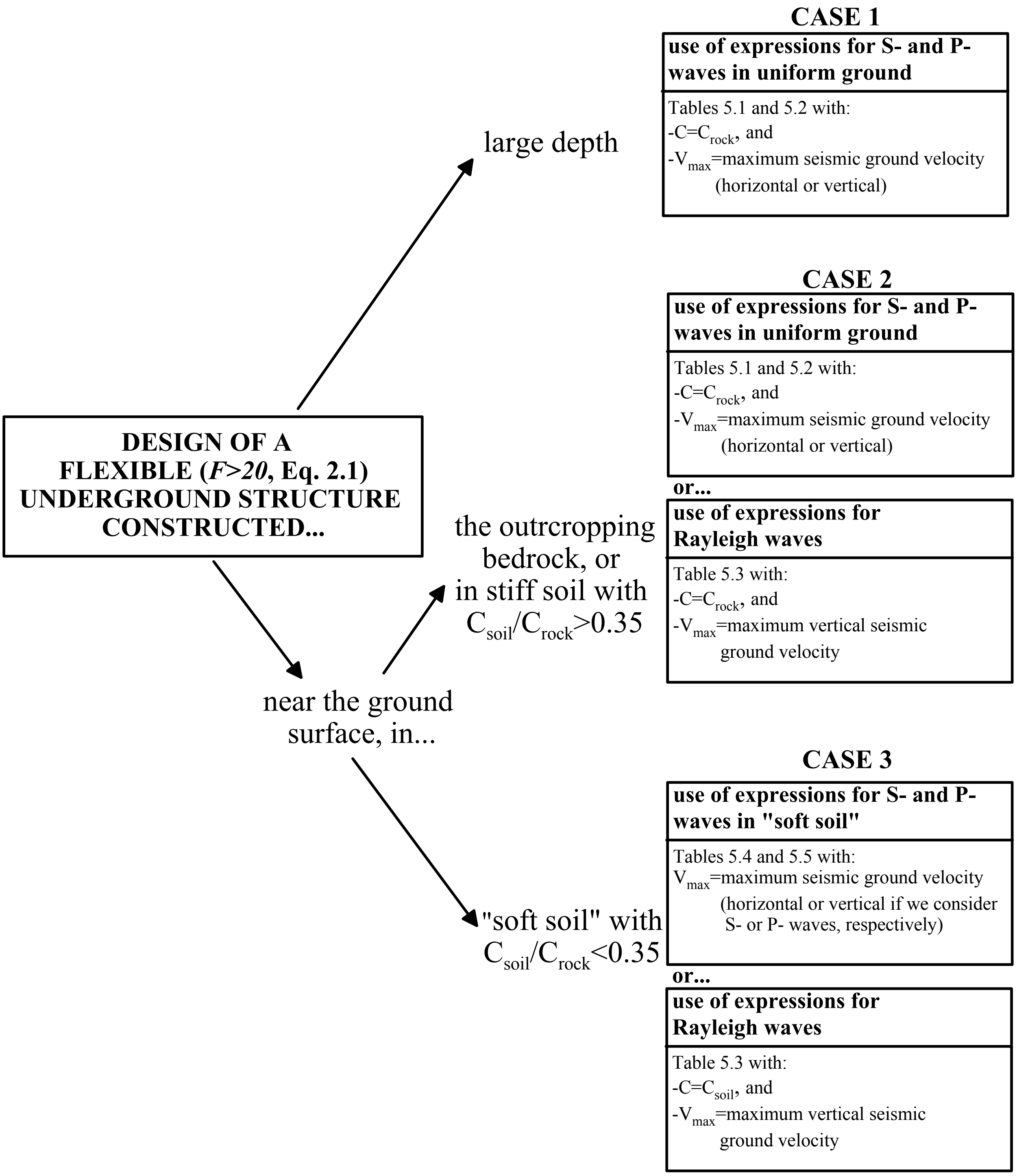

Figure 2. Flow chart for the calculation of design strains in underground structures due to seismic wave propagation.

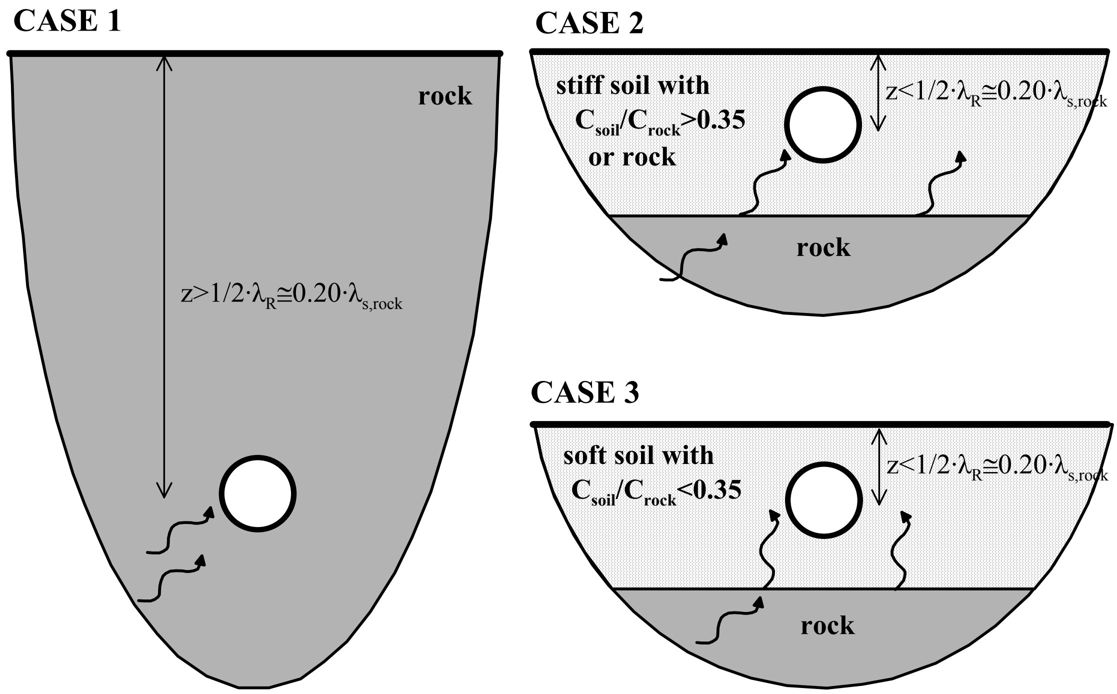

Figure 3. Classification of underground structures with respect to the local soil conditions and the depth of construction.

A vital role in the development of the design methodology against blast-induced ground shock waves, presented in the **second** part, plays the estimation of the wave type that will dominate the waveform, as well as its amplitude, for varying distances from the explosion source. Analytical solutions, empirical correlations and experimental data from the existing literature show that the strong motion attenuates exponentially with the distance from the source of the explosion, and its maximum amplitude is attributed to P waves in small and Rayleigh waves in larger distances from the center of the explosion. In the present, a series of simple expressions for the calculation of the peak particle velocity due to a surface explosion are proposed, resulting from the cross-evaluation of data from modern literature.

The analytical calculation of strains is based on the assumptions developed in the first part for seismic waves, **while taking into account that blast-induced ground waves propagate with a spherical front (Figure 1) and attenuate exponentially with the distance from the source.** The analytical expressions for strains, derived from the application of thin-shell theory, are verified against a series of 3-D dynamic FEM analyses and are accordingly maximized against the unknown parameters of the problem, so as to conclude to a set of simple, easy-to-use, design relations. The discrete steps into which the proposed methodology can be broken into are summarized in two flow charts, regarding:

- the calculation of blast-induced strains, for a given distance of the structure from an explosion source, and their consequent comparison with the allowable material strain, and (Figure 4), or
- The calculation of the minimum safety distance from a potential explosion source (Figure 5).

INPUT DATA: - explosive type and mass
- distance of the structure from the center of the explosion, d
- properties of the surface soil layer (wave propagation velocity C, grain size distribution, saturation degree S_r)
- maximum allowable strain, ε_{all}

STEP 1 -calculation of the peak particle velocity V_{max} at the projection of the center of the explosion on the structure axis

- calculation of the equivalent explosive mass W (Table 7.4)
- calculation of the coupling factor C_f (Figure 7.5)
- evaluation of the constants E, n depeding on the local soil conditions (Table 7.7)
- calculation of V_{max} at a distance d equal to the distance between the structure and the explosion source (Eq. 7.9)

↓

STEP 2 -calculation of the correction factor CF_{max} for the component of strain that corresponds to ε_{all}

- from Table 9.9 for P wave
- from Table 9.11 for Rayleigh wave

(the attenuation exponent n is taken from Table 7.7)

↓

STEP 3 -calculation of the maximum strain on the structure, ε_{bl}

$$\varepsilon_{bl} = CF_{\max} \cdot \frac{V_{\max}}{C}$$

↓

STEP 4 -check $\varepsilon_{bl}<\varepsilon_{all}$

↓

STEP 5 -if $\varepsilon_{bl}>\varepsilon_{all}$, calculate the position of the maximum z_{max} and the extent of the nessesary protective measures

- from Table 9.9 for P wave
- from Table 9.11 for Rayleigh wave

(the attenuation exponent n is taken from Table 7.7)

-use of Figures 9.5-9.6 or 9.12-9.17 for the estimation of the length of protective measures

Figure 4. Flow chart for the design of underground structures against blasts-Case A: Comparison of the dynamic strain with the maximum allowable strain, for a given distance of the structure from the blast source.

INPUT DATA: - explosive type and mass
- properties of the surface soil layer
(wave propagation velocity C, grain size distribution, saturation degree S_r)
- maximum allowable strain, ε_{all}

STEP 1 -calculation of the correction factor CF_{max} for the component of strain that corresponds to ε_{all}

- from Table 9.9 for P wave
- from Table 9.11 for Rayleigh wave
(the attenuation exponent n is taken from Table 7.7)

↓

STEP 2 -calculation of the maximum tolerable particle velocity, V_{max}

$$V_{\max} = \varepsilon_{all} \cdot \frac{C}{CF_{\max}}$$

↓

STEP 3 -calculation of the minimum safety distance, d_{min}

- calculation of the equivalent explosive mass W (Table 7.4)
- calculation of the coupling factor C_f (Figure 7.5)
- evaluation of the constants E, n depeding on the local soil conditions (Table 7.7)
- calculation of the safety distance d_{min}:

$$d_{\min} = \left(\frac{V_{\max}}{E \cdot C_f} \right)^n \cdot W^{0.333}$$

Figue 5. Flow chart for the design of underground structures against blasts-Case B: Calculation of the minimum safety distance from a potential blast source.

Main findings for the seismic wave verification of underground structures._ Evaluation of the seismic resistance of buried pipelines is based today (EC8, 2003 ASCE-ALA, 2001) on the following expression for axial strains:

$$\varepsilon_{all} > \frac{V_{\max}}{C_a} \quad (1)$$

where V_{max} is the peak particle velocity and C_a is the apparent wave propagation velocity in the seismic bedrock (≈2000m/sec). This simplified approach proves sufficient for buried pipelines and tunnels constructed with weak zones featuring a reduced strength in axial tension, such as steel pipelines with peripheral in-situ welds, where the maximum allowable axial strain is $\varepsilon_{all}=0.5\%$ (ASCE-ALA, 2001). Indeed, from the present research it is proven that the axial strain does not depend on the local soil conditions, as it is always related to the wave propagation velocity in the bedrock. The above are valid for tunnels and pipelines constructed near the epicentre, which are mainly designed against S wave action. In case we should consider the possibility that Rayleigh waves will dominate the waveform, the apparent propagation velocity in equation (1) must be replaced by the actual Rayleigh wave propagation velocity near the surface, as also noted by St John and Zahrah (1987) and O' Rourke and Liu (1999).

However, the picture drawn above is reversed when it comes to design of underground structures without specific weak zones: Numerous randomly oriented cracks (longitudinal, shear etc.) recorded in concrete tunnels and pipelines during the Kobe, Chi-Chi and Düzce earthquakes indicate that axial tension is not the predominant mode of failure for such underground structures. In fact, out of a total of 97 recorded damage cases, only 8 were had the form of peripheral cracks due to excessive axial strains. Such evidence leads to the conclusion that concrete underground structures without well-defined weak zones, but also steel pipelines with spiral welding or other type of joints, should be designed for the principal strain in the cross-section, as we cannot a-priori know the plane where the maximum tensile strain will appear.

This principal strain is computed with the proposed methodology to be 40% larger than the maximum strain calculated with the current practice (St. John and Zahrah, 1987, EC8, 2003, ASCE-ALA, 2001), for S wave action and structures in rock. This divergence is attributed to the accurate strain analysis technique incorporated in the proposed methodology, which allows for the exact superposition of strain components to calculate the principal strains.

It is also proved that the expressions providing the principal strains in the case of underground structures constructed in soft soil over rock depend on the actual wave propagation velocity in the soft soil layer, rather than the apparent wave propagation velocity in the bedrock. In this case, the relations proposed by St. John and Zahrah, EC8 and ASCE-ALA, that employ the apparent velocity of body waves (P&S), appear to be significantly un-conservative, as they underestimate the maximum strain by 5 to 6.5 times, for a ratio of wave propagation velocities in soil and rock equal to $C_{soil}/C_{rock}=0.2$.

Those findings are supported by the results of the a-posteriori analysis of damages in underground structures during the Kobe, Chi-Chi and Düzce earthquakes. By employing the proposed methodology we can predict the appearance of the 64% of total damages, contrarily to the current practice that can only predict the 9% of damages. This is attributed, in gross terms, to the fact that existing solutions overlook the effect of local soil conditions when calculating earthquake-induced strains. In support of this comes the observation that 78% of structures build in "soft soil" (where the proposed methodology predicts significantly larger strains) developed some kind of damage, contrary to the 37% of structures constructed in rock. Overall, the proposed methodology was able to predict the actual in-situ behaviour (i.e. development or not of damage) for the 74% of case studies included in the database.

Main findings for blast-induced ground shock verification of underground structures._ Modern guidelines for the design of buried pipelines against blasts (ASCE-ALA, 2001) are based on an empirical expression for calculating structure stresses, derived from the statistical analysis of a rather narrow database of experimental data from blasts near instrumented pipelines. This approach is not supported by a sound theoretical background, affirming that all aspects of the problem, such as local soil conditions, are given proper consideration. It appears, from the results of the fictitious design case presented here, that the systematic strain analysis with the proposed methodology can lead to axial strains that are 3 times larger in the area that is of interest for real world cases *(0.1<ε<4%)* and for pipelines constructed in cohesive soils. Even larger differences emerge if the design of the pipeline is based on the maximum principal strain, as it can be up to 6 times larger than that computed by ASCE-ALA guidelines.

Such differences cannot be accredited solely to the expressions employed by the proposed methodology in the estimation of the attenuation of the peak particle velocity: even when considering a pipeline constructed in saturated sand, where the attenuation relations proposed here are in fair agreement with those proposed by the ASCE-ALA guidelines, strains calculated with the current methodology still appear to be 2 to 5 times larger.

However, it should be noted that the abovementioned comparisons cannot be but indicative, as the expression included in ASCE-ALA guidelines is adapted to the mean values of the experimental data, and the guidelines suggest the, case-by-case, augmentation of this mean value, when extra levels of safety are required.

On the other hand, Dowding (1985) recommends, in the absence of any problem-specific solutions, the calculation of the axial strain in the pipeline with the expression originally derived for seismic waves with plane front:

$$\varepsilon = \frac{V_{\max}}{C} \tag{2}$$

where V_{max} is the peak particle velocity and C is the wave propagation velocity in the surface soil layer. It can be proved though that ignoring the fact that blast-induced waves propagate with a spherical front, with their amplitude attenuation rapidly with the distance from their source, can lead to overestimation of axial stains by 4 to 7 times. Although conservative, this approach is insufficient when the design objective is the calculation of the minimum safety distance of the pipeline from a potential explosion source: employing the simplified expression for seismic waves will lead to safety distances 2 to 3 times larger than the proposed methodology and, possibly, to unnecessary re-routing of the pipeline and a disproportionate increase in the cost of the project.