DEFORMATION OF BURIED PIPELINES BY SUBSOIL DETONATION

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ABSTRACT

Transport pipelines are critical for the distribution of energy commodities, refined products and essential materials like water and hydrogen. While often buried underground for protection from environmental factors, they remain vulnerable to distant threats such as intentional or accidental explosions. This study investigates the mechanical response of steel pipelines to seismic excitation from nearby buried explosive charges. An experimental approach was employed to measure the stresses and deformation of a buried, straight steel pipeline segment using high-frequency strain gauges attached to its surface before burial in damp, sandy soil. The gauges were strategically placed to capture various deformation modes, such as ovalisation and axial strain. Seismic loading was applied using buried plastic explosive charges weighing up to 16 kg TNT-equivalent, detonated at distances up to 8 m from the pipeline centre. Seismic ground shock characteristics were evaluated using triaxial MEMS accelerometers. The results establish a relationship between the explosion intensity, measured ground shock characteristics (e.g., peak particle velocity) and pipeline deformation. For the experimental scenarios, pipeline deformation remained within the elastic limit, with maximum strains measured in the order of 100 – 200 $\times 10^{-6}$. The ground shock was found to be significantly damped between the detonation point and the pipeline. Thus, when no other loads are present, transport pipelines buried in dry, sandy soil are predicted to deform elastically for subsoil detonations up to 100 kg TNT-equivalent at a 14.5-m distance.

Keywords: subsoil detonation, gas pipelines, UXOs, soft soil, safety distances, steel deformation.

1 INTRODUCTION

The Netherlands was heavily bombed during World War II (see Fig. 1). Additionally, the country served as a flight route for Allied bombers heading to Germany. On their return flights, bombers often dropped unexploded bombs in so-called safe areas to save fuel. Many of these bombs never detonated (named UXOs (UneXploded Ordnance), also known as duds) and remain in the Dutch soil. These duds are frequently discovered, particularly during construction works, by specialized detection companies. Once these unexploded remnants of war have been localised, the Dutch Army Explosive Ordnance Disposal Regiment (EOD) is called in to neutralize the threat in the safest possible way.

Although the safest possible way of neutralising the UXO is aimed for, for adequate safety measures to be taken during the dismounting intervention, one must consider the possibility that the UXO unfortunately will detonate. Therefore, evacuations of people and feedstock may be necessary, and possible damage to neighbouring structures must be considered.

The damage due to undesired detonation of such UXO may be caused by fragments, blast and seismic effects of the detonation, the so-called ground shock. The first two damage causes are in The Netherlands' EOD practice mitigated by covering the UXO by a temporary large heap of sand, which will on the other hand increase the coupling of the UXO to the soil, hence increasing the ground shock effect. For the ground shock effects safety distance tables are used, which consider the size of the charge, the local soil characteristics and the ground water level, amongst others. However, for these safety distances of underground detonations

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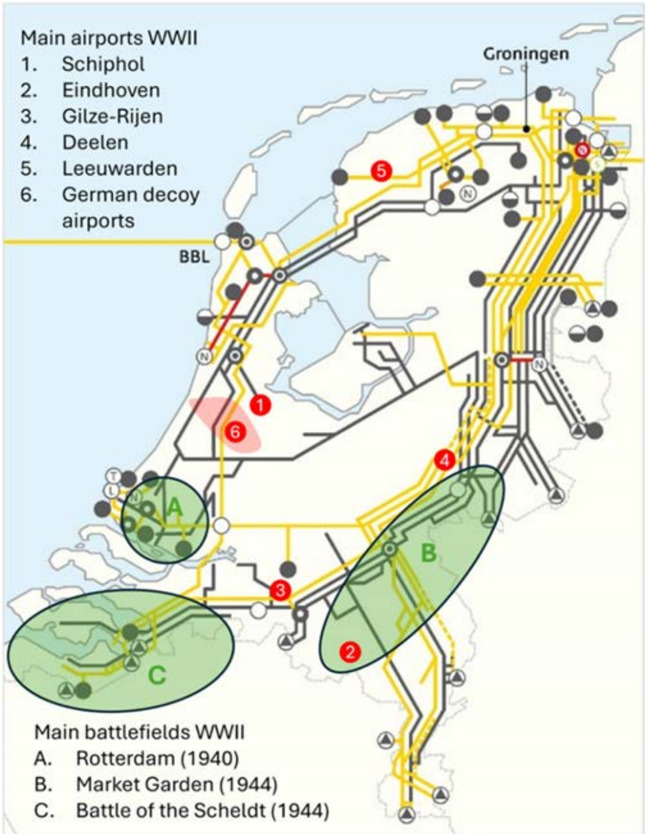

Figure 1: The high-pressure gas network in The Netherlands. Also shown are the main airports and battlefields in World War II. *(Source: Gasunie Transport Services and Dutch Army Explosive Ordnance Disposal Regiment.)*

different criteria exist, depending on whether it is the owner of some sort of (critical) infrastructure or the Dutch EOD. Discrepancy in these safety distances arises partly due to a lack of empirical knowledge about the impact of ground shock on pipelines, particularly in Dutch soil. The Netherlands has highly variable soil conditions, ranging from dry sands to saturated clays, which further complicates the assessment. Research is needed to better understand these effects and therefore the development of experimentally validated prediction methods for determining safety distances. Such knowledge could also benefit the design of underground infrastructure near industrial facilities where explosion risks exist, such as fuel or hydrogen storage terminals. Relatively few similar studies in this field exist, for example [1]–[3].

For instance, pipeline owners have an interest in a validated method, as their current approach – dating back to the 1980s – is necessarily conservative. This may lead to unnecessary protective measures, such as depressurizing pipelines, installing sheet piles, or digging trenches, all of which are costly. Additionally, shutting down a pipeline temporarily can have significant societal impacts. A scientifically grounded safety distance would eliminate unnecessary precautions while ensuring public safety.

To acquire empirical knowledge, ten detonation experiments have been performed, see Table 1. In all these experiments 10-inch straight steel tubes without internal pressure – representing pipelines – were used, in one type of soil. The ground shock characteristics are measured using triaxial MEMS sensors and the deformation of the pipeline was measured using strain gauges. For all experiments, a common plastic military explosive was used. The explosive material was used without any casing. The latter could decrease the effect of the shock wave upon the pipeline.

Table 1: Overview of the performed experiments. For each experiment, the mass of the plastic explosive, its distance from the steel pipeline and its location of the detonation is given.

Detonation	**Mass explosive (kg)**	**Distance (m)**	**Location of detonation**
1	2.5	5	Perpendicular; middle pipe
2	4	8	Perpendicular; middle pipe
3	2.5	4	Extension of pipeline
4	4	4	Extension of pipeline
5	3.5	5	Perpendicular; middle pipe
6	3.5	5	Perpendicular; end pipe
7	5	5	Perpendicular; middle pipe
8	5	5	Perpendicular; middle pipe
9	10	5	Perpendicular; end pipe
10	10	5	Perpendicular; middle pipe

The structure of this paper is as follows. First, some theoretical background is given. Next, the experimental set-up and the materials used are described. Then, results of the experiments, i.e., the mechanical response of the pipeline, is discussed. This is followed by conclusions and recommendations for future research in this topic.

2 THEORETICAL BACKGROUND

2.1 Deformation in longitudinal direction

The characteristics of the ground shock wave originating from the explosive charge will be treated as the loading of the pipeline segment. Details of this wave, i.e., whether it has a surface wave character etc. [4], are not considered here. Only the measured strength of the wave, as measured close to the pipe segment, is considered as the load. Compression and shear wave components of the ground shock introduce strain in both the longitudinal (L, axial) and circumferential (C) directions of the buried transport pipeline. Shear waves, and possibly compression waves, depending on the angle of impact on the pipeline, result in axial strain in the pipeline. This leads to the development of tensile and compressive stresses within the pipeline. The axial strain can be calculated using:

$$\varepsilon_{aL} = \frac{u}{c_p} \cos\theta. \quad (1)$$

In this equation u is the peak particle velocity, c_p the propagation velocity of the compression wave, and θ the angle between de location on the pipeline and the detonation [5].

Additionally, shear waves, and possibly compression waves, will cause bending strain due to difference in arrival of the shear and compression waves over the length of the pipeline. Assuming the bending of the pipe follows the deformation of the surrounding soil, the strain caused by bending can be calculated as follows:

$$\varepsilon_{bL} = \frac{u(2\pi f)d}{2c_s^2}\cos\theta. \tag{2}$$

In this equation d is the outer diameter of the pipeline, f is the dominant frequency of the shear wave, and c_s the propagation velocity of the shear wave [5], [6].

2.2 Deformation in circumferential direction: Ovalisation

The circumferential strain occurs because of loading by the compression wave component of the ground shock. The maximum circumferential strain can be estimated using the maximum strain caused by the compression wave, plus a small additional strain due to bending caused by the ovalisation – i.e., the deformation that leads to change of shape of the pipe segment's cross section – of the pipeline. The circular strain can be obtained from:

$$\varepsilon_h = \frac{u}{c_p}\left(1 + \frac{3t}{d}\right)\sin\theta, \tag{3}$$

in which ε_h is the circular strain and t is the thickness of the pipe [5].

2.3 Damping characteristics of the ground shock

The Bornitz equation [7] describes the two most important factors of the attenuation of intensity of the ground shock with distance: material damping and geometric damping. Here we formulate the Bornitz equation for a chosen strength parameter, the peak particle velocity (PPV) of the ground shock, at a distance r from the detonation location

$$v(r) = v(r_0)\left(\frac{r_0}{\mathrm{r}}\right)^n e^{-\alpha(r-r_0)}. \tag{4}$$

In this equation $v(r)$ and $v(r_0)$ are the peak particle velocities at distance r and a reference distance r_0 from the source. α is the decay or attenuation coefficient. This coefficient is dependent on material characteristics of the soil. In addition, it is dependent on the dominant frequency f of the vibration:

$$\alpha = \frac{2\pi D f}{c}. \tag{5}$$

In this equation c is the propagation velocity of the waves, and D is the so-called damping ratio. Finally, the parameter n determines the geometric damping (e.g., $n = \frac{1}{2}$ for surface waves). Thus, by measuring the PPV at a reference distance r_0, the expected PPV can be calculated for any distance r, provided that α and n are known.

Often seismic loading is given in terms of the local acceleration as determined by vibration sensors. However, in Dutch norms [8] iso-damage distances are related to peak particle velocities, which explains the choice for this metric for the seismic loading.

3 EXPERIMENTAL

To investigate the response from a buried pipeline to transient loading from an underground detonation, ten detonation experiments have been performed, see Table 1. In all these experiments a straight pipeline segment was used. Fig. 2 provides details of the experimental set-up that has been used.

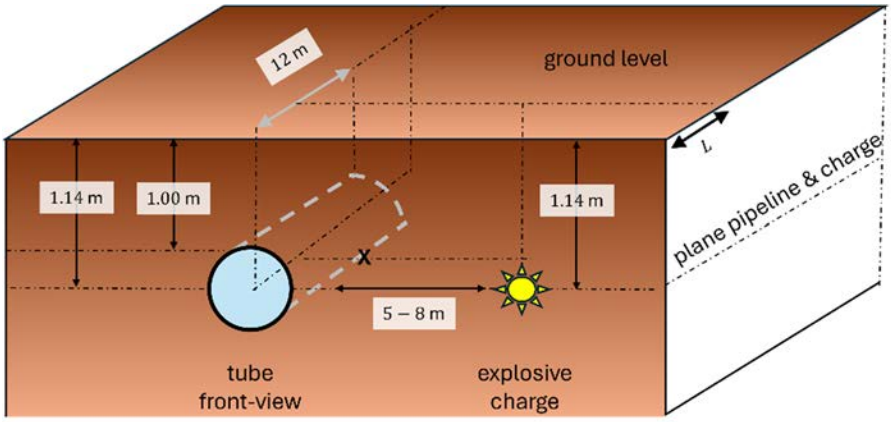

Figure 2: Overview of the experimental set-up: pipeline and explosive charge buried in damp sandy soil. The X shows the location of the MEMS-seismic sensor whose data are shown in Fig. 5(a) (the sensors are buried at 1.14 m below ground level).

3.1 Buried steel pipeline

The buried, steel (L245MB) pipeline segment has a total length of 12 m and a circular cross section with an outer diameter of 273.0 mm, and a nominal wall thickness of 6.3 mm. After the strain gauges were placed, the two parts were welded together. The specified minimum yield strength of the pipeline steel is 245 MPa and its tensile strength is 466 MPa, as obtained from tests on a 20 mm wide specimen [9]. For transport and placement two lifting eyes were welded to the pipe. While hanging in free air and excitation of the pipe with a steel hammer, the only observable eigenfrequency of the pipeline segment was found about 10 Hz.

3.2 Seismic loading

For the experiments a plastic explosive consisting of 83% penthrite was used with a mass density of 1,770 kg/m^3 and a detonation velocity of 8,350 m/s. The specified explosion temperature is 4,230°C, and its mass specific energy 5,800 kJ/kg. The relative effectiveness factor of this form of penthrite is close to 1.25 [10]. Usually, one performs this type of experiments at constant depth of burst, i.e., at constant $d/\sqrt[3]{w}$, with d the depth relative to ground level, and w the TNT-equivalent mass of the explosive charge [9]. However, here it’s chosen to have the pipeline and explosive charge buried at the same depth. After burying the charge, the hole is filled with sand, and finally all is covered with a heap of sand to achieve optimal coupling between the charge and the soil. It also should be noted, especially when detonations take place at the same location, that experiments will locally compact the soil, which leads to different soil properties – hence, shock propagation properties – in subsequent tests.

3.3 Ground shock seismic properties and pipeline response

Triaxial MEMS accelerometers or vibration sensors (Convergence Instruments) with a dynamic range of 8*g* are used to measure the PPV of the ground shock that originates from the detonation. The sensors record the particle velocity of the ground wave along three orthogonal axes. The convention was adopted that the sensor's *x*-axis was oriented from the point of detonation perpendicular to the pipeline, its *y*-axis parallel to the longitudinal direction of the pipeline, and the *z*-axis is perpendicular to the ground level. The sensors are buried in the ground such that their *xy*-plane coincides with the plane defined by pipeline and explosive charge. The vibration sensors were operated at a signal sampling rate of 1000 Hz, and were set to measure in the velocity mode, providing the particle velocities for all three directions. From this, the PPV is readily determined.

Six vibration sensors are used in this experiment. Three of these sensors were placed in front of the pipeline, positioned close to it. One sensor was placed at the rear of the pipeline, also positioned close to it. Finally, two additional sensors were placed behind the detonation site. For the experiments reported here, the sensor indicated with X – between detonation location and pipeline (see Fig. 2) – was used. Moreover, the sensors are also used to measure the ground shock propagation properties of the soil. For this the sensors internal clocks need to get mutually synchronised prior to experimentation. For the sandy soil as present at the experiment location (‘t Harde, the Netherlands), a seismic velocity of 426 m/s and wavelength of about 85 m (frequency of 5 Hz) was found.

Precision strain gauges (Micro Measurements, USA) are used to measure the strain in both the longitudinal (L) and circumferential (C) directions of the pipeline. They are carefully attached to the pipeline, so that any deformation of the pipeline is transferred to the strain gauges as well. The strain gauges are connected to a power source, and when the strain gauges deform, their resistance changes accordingly. Finally, the local strain as function of time is obtained by measuring the changes in electrical resistance at 1 kHz. The measured strain can be converted into mechanical stress, allowing for the determination of the stress occurring in the pipeline. The strain gauges used in this experiment are so-called T-rosettes. They consist of two strain gauges positioned at a 90° angle to each other.

Fig. 3 shows the strain gauges used in this experiment and the way they are mounted to the pipeline. In Fig. 4, the locations of the eight strain gauges attached to the pipeline segment are indicated.

4 MECHANICAL LOADING AND RESPONSE

Now the most important experimental results are given. Here we focus on extreme values found for the measured strains, as they are important to obtain objective estimates for safety distances. Fig. 5 shows the mechanical loading and strain response at various locations, for scenario 10 as presented in Table 1. Table 2 presents the experimentally obtained loading results from the vibration sensors, i.e., the peak particle velocities resulting from the ground shock, measured in the *x*-, *y*-, and *z*-directions as described in Section 3. In Fig. 5(a) it is shown how the PPV is obtained, and in Table 2 the PPVs are given for the seven accelerometers installed. Sensor 1 has the highest value of PPV. This is the sensor represented by an X in Fig. 2, and which PPV is being used in the remainder of this paper. The wobbly pattern observed in Fig. 5(b) is observed in all T-rosettes and happens to have a frequency of about 50 Hz. It is considered as a measurement artifact, that will not be further elaborated here.

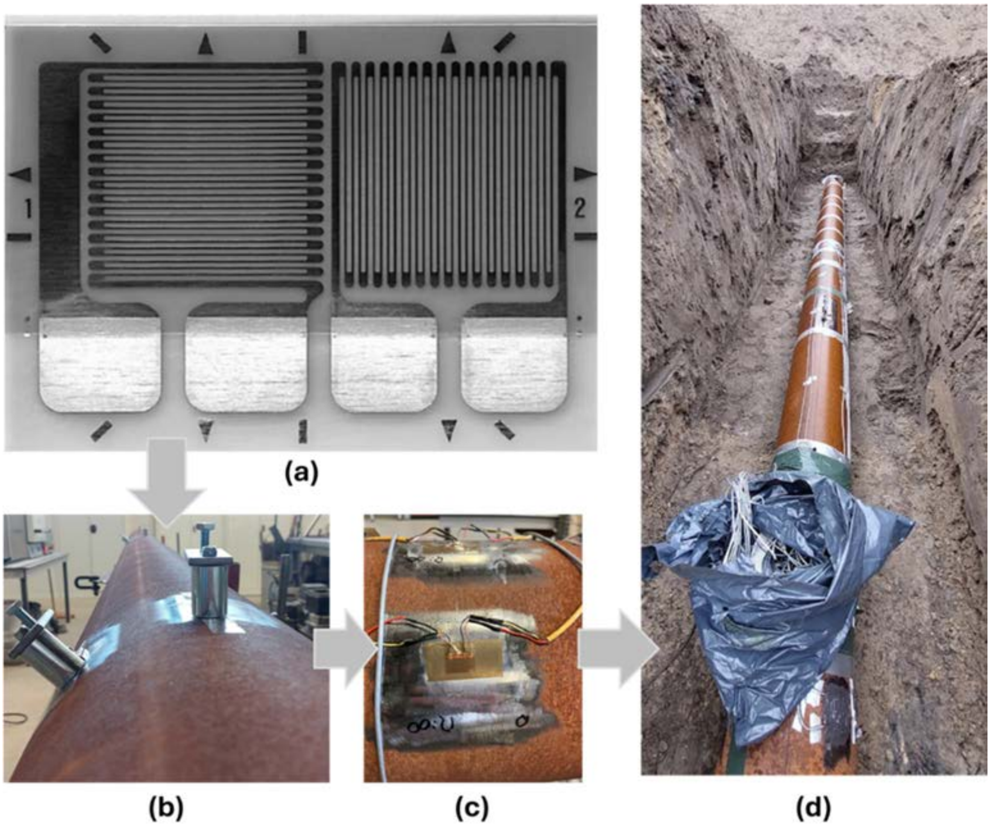

Figure 3: (a) General purpose strain gauge (Tee Rosette 250UT with resistance $(350 \pm 0.4\%)\Omega$; (b) Mounted to a polished area of the pipeline, coated and press-dried; (c) Wired pipe-gauges system; and (d) Finally at the test site (with protective cover).

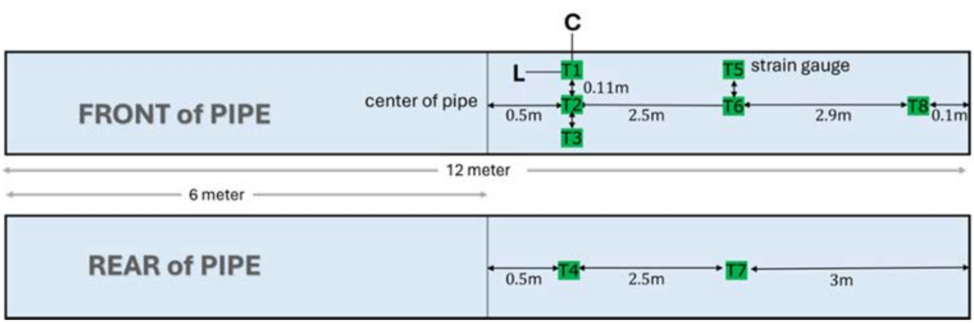

Figure 4: Location of strain gauges (T1–T9) at the front (directed to incoming ground shock) and rear of the pipeline. The bold L (length of the pipe direction) and C (circumferential direction) identify the strain measuring directions of the gauges. Front of pipe means the face of the pipe directed towards the detonation location.

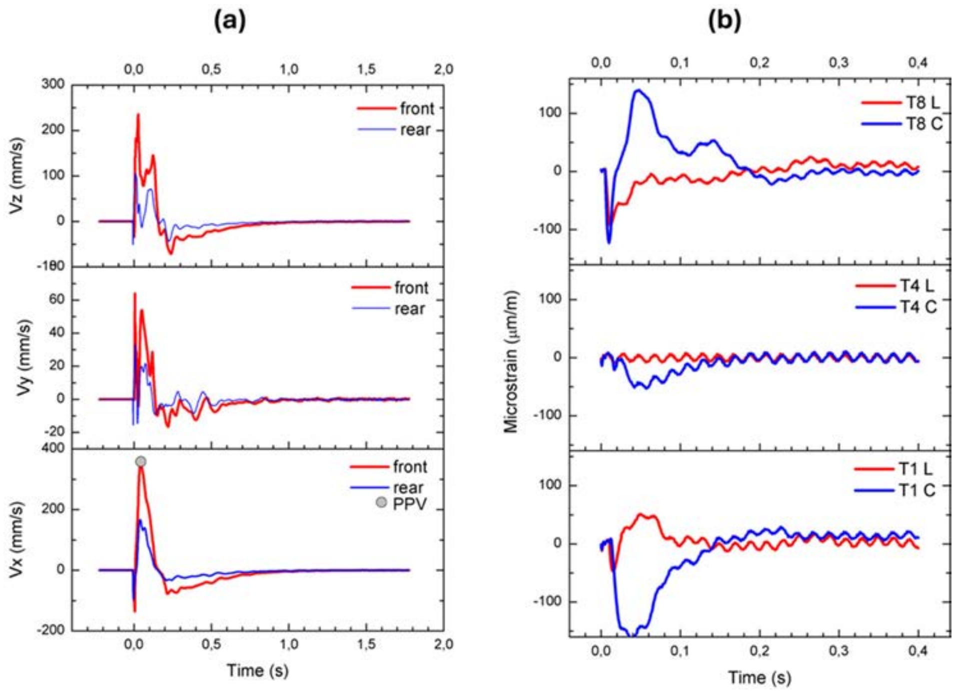

Figure 5: Loading and strain response of a 10 kg charge. (a) Measured seismic particle velocities just in front and behind (rear) the pipeline; and (b) Axial (L) and radial (O) deformation (strain) as measured at various locations (T1, T4, T8).

Table 2: Peak particle velocity of the vibration sensors for Detonation 10. For each sensor the distance to the detonation is given.

Sensor	Peak particle velocity x-direction (mm/s)	Peak particle velocity y-direction (mm/s)	Peak particle velocity z-direction (mm/s)	Distance to detonation (m)
1	378.4	62.55	251.9	5.0
2	228.8	147.9	118.2	5.6
3	48.17	79.51	102.4	7.4
4	174.7	33.75	109.7	5.5
6	29,44	15.78	73.76	8.0
7	34.18	15.23	36.04	17.25

In Figure 6, the observed strains and the corresponding calculated stresses, from Hooke's law and Equations (1) to (3), are presented. During the experiment, strain measurements were taken at select number of points on the pipeline, as shown in Figure 4. Therefore, the strain in the remaining sections is an estimation. The strain is given in micro strain, i.e. 10^{-6}, and the stress is measured in MPa. Strain is treated as a positive value, as the focus is primarily on the magnitude rather than the direction in which it occurs. However, for stress, also the negative strain values were considered, and the stress values shown in the figure represent the absolute values.

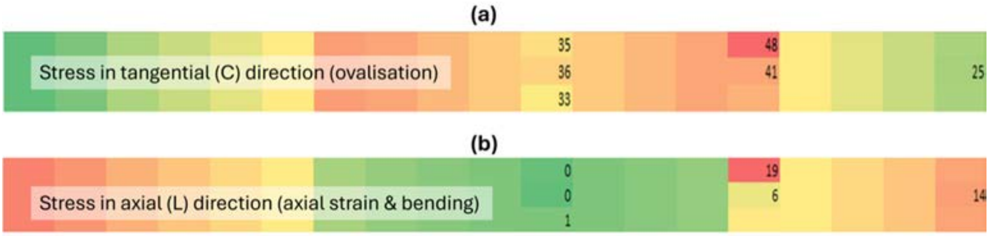

Figure 6: Schematic view of the stresses in the pipeline for Detonation 10. The values that have been measured are shown. For other locations the values are estimated.

Table 3: Peak particle velocity and maximum strain for Detonation 10. Strain in longitudinal direction is indicated with an L and strain in the circumferential direction is indicated with a C.

Sensor & strain gauge	Peak particle velocity x-direction (mm/s)	Peak particle velocity y-direction (mm/s)	Peak particle velocity z-direction (mm/s)	Maximum strain L (µ)	Maximum strain C (µ)	Distance to detonation (m)
1 & T2	378.4	62.55	251.9	53	−174	5.0
2 & T6	228.8	147.9	118.2	87	−205	5.6
3 & T8	48.17	79.51	102.4	−102	139	7.4
4 & T4	174.7	33.75	109.7	−17	−60	5.5

It is interesting to compare the peak particle velocity of the seismic waves with the deformation in the pipeline, as this provides a better understanding of the response of the tube (see Table 3).

For Detonation 10 (Table 1), the largest deformation on average occurs in the circumferential direction at strain gauge T5. However, this does not automatically mean that the highest stress also occurs at the location of strain gauge T5. The largest deformations and, consequently, stresses may also have occurred in sections of the pipeline where no strain gauges were placed.

For strain gauges T5 and T7, it is possible to plot a linear relationship between the peak particle velocity at vibration sensor 1 (located at X in Fig. 2) and the maximum occurring strain in both the longitudinal and circumferential directions. Results are shown in Fig. 7. From these graphs, it can be observed that for strain gauge T5, the longitudinal strain increases in the positive strain direction as a function of peak particle velocity, while the circumferential strain increases in the negative strain direction. For strain gauge T7, both the circumferential and longitudinal strains increase in the negative strain direction as a function of peak particle velocity.

So, two possible stress states of the pipeline are observed: one where the strain in the circumferential and longitudinal directions essentially compensate each other, shown in the lower graph in Fig. 7, and one where the strain in the longitudinal and circumferential directions reinforce each other, shown in the upper graph in Fig. 7.

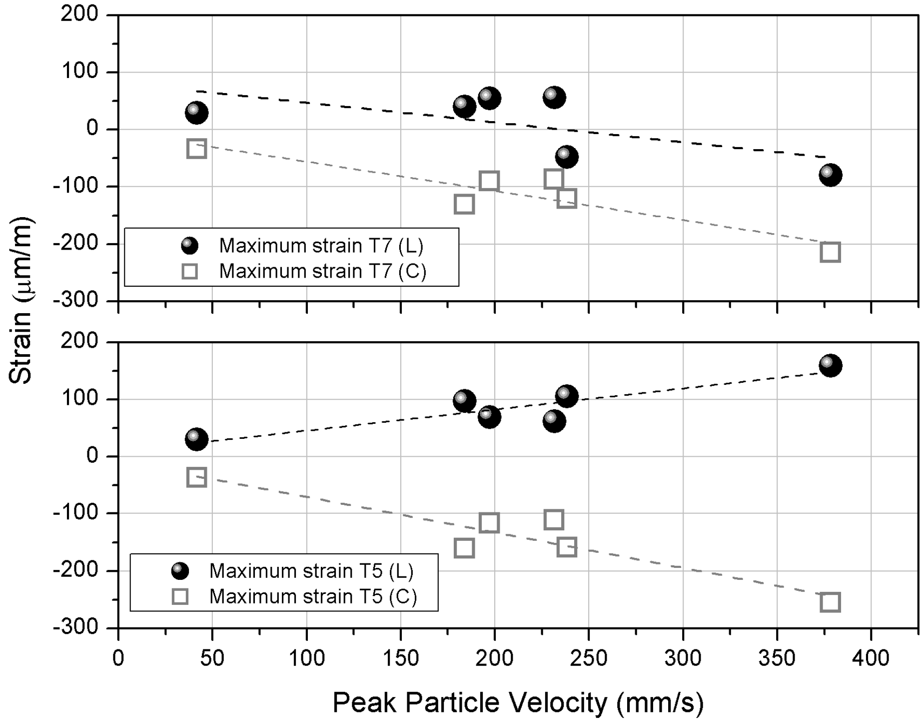

Figure 7: Maximum strain in longitudinal (L) and circumferential/tangential (C) direction as a function of the PPV measured by vibration sensor 1.

5 CONCLUSIONS

This research investigates the relationship between ground waves caused by underground detonations and the resulting stresses in buried transport pipelines. Based on the literature reviewed and experimental results, the study confirms that such a relationship exists. Two types of ground waves are generated by underground detonations: compression waves and shear waves. Among these, compression waves cause the most significant deformations and, consequently, the highest stresses in pipelines. Shear waves can amplify this effect. The most critical scenario occurs when a detonation charge is positioned perpendicular to the pipeline, and the explosive charge is highest

The study identifies three main deformation modes leading to stress in the pipeline: bending, axial tension and compression, and ovalisation. There are also two different stress scenarios. The highest stress occurs when both circumferential and longitudinal strains are either positive or negative. When one strain is positive and the other negative, the resulting stress is lower.

For the specific pipeline studied, a correlation was found between peak particle velocity of the ground waves and the induced stress. The highest stress was observed at strain gauge T7, where both circumferential and longitudinal strains were negative (see Fig. 7). At a peak particle velocity of 378 mm/s, a maximum stress of 55 MPA was recorded, which remains well below the pipe's yield strength. To exceed the yield limit of 245 MPa, a detonation would need to generate a peak particle velocity of 1,877 mm/s, equivalent to a 100 kg TNT explosion at 14.5 m from the pipeline, assuming similar soil conditions.

In conclusion, while a relationship between detonation-induced ground shock waves and pipeline stress is evident, it remains difficult to quantify precisely due to the problem's complexity. This research treated it as a static issue, although it is inherently dynamic. Since strain varies along the pipeline and strain waves may propagate along the pipeline segment. Moreover, deformations can occur in multiple ways, which makes a direct correlation to be challenging. However, the study confirms that higher peak particle velocities lead to greater deformations and higher stress levels, However, when a maximum allowed stress level is defined, e.g., as a percentage of the yield stress, a good estimate of safety distances can in principle be derived from the experiments presented. However, it should be noted that these experimental results provide a lower limit to the deformation of the tube. The experiments were conducted in dry sand (high seismic damping), while the tube had a high thickness-to-diameter ratio. Smaller ratios, occurring for large-diameter transport lines, will probably lead to larger deformations.

Therefore, additional experiments are planned in the future. Moreover, finite element simulations may further clarify the relation between seismic waves and the stresses and deformations they cause in buried pipelines.

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