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Safety of buried steel natural gas pipelines under earthquake-induced ground shaking: A review

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ABSTRACT

Evidence from past earthquakes suggests that damage inflicted to buried natural gas (NG) pipelines can cause long service disruptions, leading to unpredictably high socioeconomic losses in unprepared communities. In this review paper, we aim to critically revisit recent progress in the demanding field of seismic analysis, design and resilience assessment of buried steel NG pipelines. For this purpose, the existing literature and code provisions are surveyed and discussed while challenges and gaps are identified from a research, industrial and legislative perspective. It is underscored that, in contrast to common belief, transient ground deformations in non-uniform sites are not necessarily negligible and can induce undesirable deformations in the pipe, overlooked in the present standards of practice. It is further highlighted that the current seismic fragility framework is rich in empirical fragility relations but lacks analytical and experimental foundations that would permit the reliable assessment of the different parameters affecting the expected pipe damage rates. Pipeline network resilience is still in a developing stage, thus only few assessment methodologies are available whereas absent is a holistic approach to support informed decision-making towards the necessary mitigation measures. Nevertheless, there is ground for improvement by adapting existing knowledge from research on other types of lifeline networks, such as transportation networks. All above aspects are discussed and directions for future research are provided.

1. Introduction

Natural gas (NG) is nowadays a cornerstone in supplying energy to industry and households, maintaining an important share in the global energy market. A steadily growing dependence of the global energy demand on NG is reflected in numbers: one quarter of the total energy demand in the US and the European Union is currently satisfied by NG delivery [1], while it is projected that by 2040 nearly one quarter of the global electricity will be generated by NG [2]. Extensive onshore networks of buried steel pipelines are the method of choice for inland NG distribution from wells to end-users, with steel being used almost exclusively for the large-diameter transmission network. For further details on NG pipeline technology, the interested reader is referred to Folga [3].

However, of the heaviest dependents on NG are earthquake-prone regions, such as California in the United States, south-eastern Europe (Italy, Greece, Turkey and the Balkans), Japan and New Zealand, which are all exposed to significant seismic hazard. Experience from past earthquakes has repeatedly demonstrated that buried pipelines are vulnerable to seismic effects. In line with existing literature, these seismic effects can be divided into two main groups of 'geohazards', based on the temporal nature of the damage source: (a) transient ground deformation (*TGD*) due to seismic wave propagation, and (b) permanent ground deformation (*PGD*), with possible failure causes being active fault movements, landslides, liquefaction-induced settlement or lateral spreading (Fig. 1). Most of the damage reported to date is attributed to PGD [4,5], but there is also strong evidence that wave propagation has contributed to pipe damage [6–12], though to a lesser extent.

From a system-wide viewpoint, the impact of a seismic shock on the network level of a NG pipeline system can be highly adverse and spatially dispersed. A potential long-lasting flow disruption due to earthquake damage can have excessive direct and indirect socioeconomic repercussions not only locally, but also internationally, given the spatial dimension of a NG network. Records on the number of NG network users that experienced service disruption and the disruption duration after past earthquake events can be found in relevant reports [5,7,12,13]. Additionally, content leakage may have life-threatening consequences if ignition is triggered and can pose an environmental threat. It becomes therefore evident that underground NG networks traversing seismically active areas are exposed to seismic risk and, consequently, securing their long-term integrity and operability with

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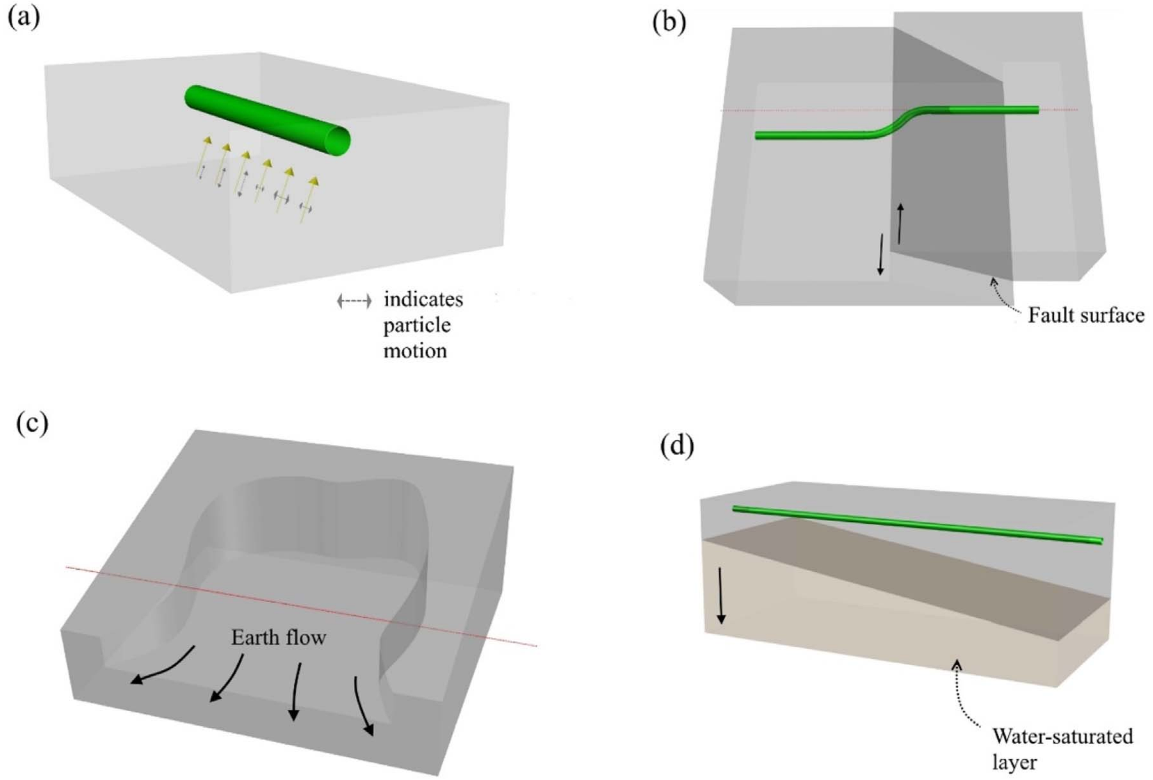

Fig. 1. Illustration of the major geohazards threatening the structural integrity of buried NG pipelines: (a) seismic wave propagation; (b) – (d) PGD types: (b) strike-slip fault movement; (c) landslide in the form of earth flow; (d) liquefaction-induced settlement.

the minimum cost to society and economy is of paramount importance. This very objective has given rise to the concept of *resilience* in recent years, which is commonly perceived as the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back, or the ability to resist, adapt to and recover from some shock, insult or disturbance. As resilience is of paramount importance for all lifeline systems, strategies for improvement are gradually being adopted as a desired target by authorities and influential movements within policy-making for natural disaster mitigation in urban environments.

Given the above challenges, the objectives of the present review study are to:

a) Identify and examine one by one essential aspects pertaining to the seismic safety of buried steel NG pipelines, both on the component and the network level. These aspects are identified by the section titles following,
b) For each element of this analysis, point out and discuss the most important outcomes and conclusions found in the literature that relate to the way we design and assess NG buried pipeline networks in seismogenic regions,
c) Highlight the primary challenges involved in each subdomain in light of the latest knowledge and pinpoint limitations and gaps that need to be filled by new research.

Analyze interrelationships among the different elements, where possible and discuss ideas for possible future research work, more so towards an integrated seismic resilience assessment framework.

The novelty herein lies in the fact that we attempt to approach the most critical aspects of seismic safety of buried NG pipelines in a holistic manner. Previous similar efforts on pipelines (e.g. [14–17]) or with a broader structural typology scope [18,19] dealt only with specific aspects independently of one another, such as response analysis and design or fragility analysis. It must be emphasized that the scope is focused on TGD effects. The reasons are that TGD involves more complex physics and more uncertainties, it is statistically more likely to affect buried pipelines due to its spatially distributed character, it is not as well documented as PGD cases and, in contrast to the above, it is often overlooked. On the other hand, pipelines under PGD is a well-developed topic supported by a large volume of analytical and experimental studies, especially in recent years. However, throughout this text, references to research explicitly dealing with PGD are also made, because these two seemingly different types of ground movement (TGD and PGD) share some common characteristics, as explained later. References to some studies on water mains are also made when the material used is steel to provide a better insight in the phenomena studied.

The structure of the study is as follows. First, five interlinked aspects of seismic safety of buried NG pipelines are reviewed in detail in a bottom-up order, starting with component and ending with network features, namely: (a) governing failure mechanisms and relevant field observations; (b) pipe response analysis elements, including soil-pipe interaction (SPI), spatial variation of seismic ground motion along the pipeline and applicable analysis methodologies; (c) seismic vulnerability of NG pipelines; (d) structural health monitoring; and (e) seismic resilience at the network level. Then, existing seismic code provisions for pipeline design are critically assessed to determine to which extent they address the latest research findings. Finally, unaddressed issues are outlined and discussed altogether, and suggestions are made for future research and improvement of existing codes.

2. Dominant failure modes and associated criteria

In the course of earthquake-resistant design of underground steel pipeline networks, one has to first identify the principal mechanisms leading to pipe failure due to seismic excitation in order to establish appropriate performance criteria and select effective analysis methodologies. Extensive previous research efforts and field surveys have been successful in classifying the most frequently occurring failure