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EARTHQUAKE DAMAGE TO BURIED PIPELINES NEAR A FAULT: A CASE STUDY IN HVERAGERÐI DURING THE 2008 M6.3 ÖLFUS EARTHQUAKE

A. Sigfúsdóttir(1), R. Rupakhety(2), S. Ólafsson(3)

(1) *PhD candidate, Earthquake Engineering Research Centre, University of Iceland, aldiss@isl.is*
(2) *Associate Professor, Earthquake Engineering Research Centre, University of Iceland, rajesh@hi.is*
(3) *Research Professor, Earthquake Engineering Research Centre, University of Iceland, simon@hi.is*
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Abstract

A strong earthquake with moment magnitude 6.3 occurred in South Iceland on 28 May 2008. This earthquake caused a lot of damage to the buried pipelines in the small town of Hveragerði, which lies very close, about 3-4 km, from the epicentre of the causative faults of the earthquake. The damages sustained by the pipelines were very well recorded in video footages obtained from camera-mounted robots that were passed through all the buried ~~pipelines~~ waste water pipelines in Hveragerði. A detailed inspection, analysis, and classification of the damages recorded in the video footages have revealed many interesting phenomena. It was observed that the most common type of damage is due to circular cracks in the pipes. Damages due to crushing of bell-spigot connections between the pipes were also very frequent. Such damages were more frequent in brittle joints which consist of cement-sand mortar, but significantly lower in flexible joints consisting of rubber gaskets. It was also observed that several improvements in concrete pipe manufacturing in Iceland that were introduced around the year 2000 improved the seismic performance of the pipes greatly. Damage rates in the new pipes were half of that in the older pipes. It was observed that the sewage pipes and the drainage pipes, which are similar in construction material and size, suffered very different damage rates, the former only suffering half the damages (per unit length) suffered by the latter. The repair rates estimated from ground motion recorded in the town along with standard fragility curves were found to significantly under-estimate damage rates suffered by the pipes in Hveragerði. The observed rates of major damages are about six times higher than the upper bounds estimated from standard fragility curves. This indicates that seismic risk management of underground lifelines in the South Iceland lowland should not rely on standard fragility curves calibrated elsewhere, but rather on local data and observations. The efforts made in detail recording and analysis of the damages suffered by the pipelines in Hveragerði during the Ölfus Earthquake is an important contribution in this regard. It is also an important lesson for other parts of the world to systematically collect and analyse damage data after major earthquakes.

Keywords: lifelines, seismic damage, repair rate, Ölfus Earthquake, fragility functions

1. Introduction

Damage to lifelines during earthquakes are caused by two main physical phenomenon related to ground shaking: wave propagation effects permanent ground deformation (PGD) effects. The damages due to wave propagation is related to deformation caused by transient passage of ground-motion waves in the vicinity of the pipes. Damages resulting from PGD effects are due to pseudo-static effects such as landslides, liquefaction induced lateral spread, surface faulting, or settlement induced by ground shaking. Damages due to PGD are usually more severe than those resulting from seismic wave propagation; the latter are generally distributed for a larger spatial extent [1]. Axial strain is assumed to be the main cause of pipeline damage due to seismic wave propagation [2]. Damage to segmented buried pipe has been found to be strongly related to ground strain [3]. Assuming compatibility of deformation between the pipe and the ground (no slippage), the maximum axial strain induced in the pipe is related directly to peak ground velocity.

Particle motion perpendicular to the axis of the pipe causes bending strain which is directly related to peak ground acceleration. This holds as long as no slippage occurs between the pipe and surrounding soil. Otherwise the pipe strain is somewhat less than the ground strain. A shear wave travelling along the pipeline produces only bending strain in the pipe. It the wave is travelling perpendicular to the pipe, only axial strains are produced. For other angles of wave propagation with respect to the pipe axis, both axial and bending strains are induced, the former being maximum for an angle of 45° [4].

This contribution presents the preliminary findings of an ongoing study concerned with a detailed analysis of damages suffered by underground pipes in the town of Hveragerði during a moment magnitude 6.3 earthquake that occurred in South Iceland on 28 May 2008. A brief introduction of the study area is provided along a description of the salient features of strong ground motion recorded in the town. Classification of damages into different mechanisms and severity are then presented, identifying the most common types of damages. A discussion on the actual damages suffered by the pipes compared with estimates obtained from commonly used pipe fragility functions is also provided.

2. Case study area

2.1 Study area and the Ölfus Earthquake

This study is based on the pipeline damage data collected in Hveragerði, a small town in South Iceland during the May 2008 Ölfus Earthquake. It is about 3.0 km^2 in size has about 2300 inhabitants. Hveragerði (see Fig. 1) lies in the South Iceland Seismic Zone (SISZ) where the most destructive earthquakes in Iceland have occurred.

The Ölfus Earthquake happened on 29 May 2008. The CMT and INGV estimated the moment magnitude of the earthquake to be 6.3. The Earthquake can be characterized as a shallow crustal event on nearly vertical north-south trending right-lateral strike-slip faults. No clear evidence of the causative fault was visible on the surface, which is due to the presence of relatively thick sediments over the bedrock [5]. The rupture is believed to have started on the Ingólfsfjall Fault (see Fig. 1), followed approximately1s later by another rupture on the Kross Fault [5]. The epicentre of the earthquake was between the towns of Selfoss and Hveragerði (see Fig. 1). The macroseismic epicentre was 3-4 km southeast of Hveragerði.

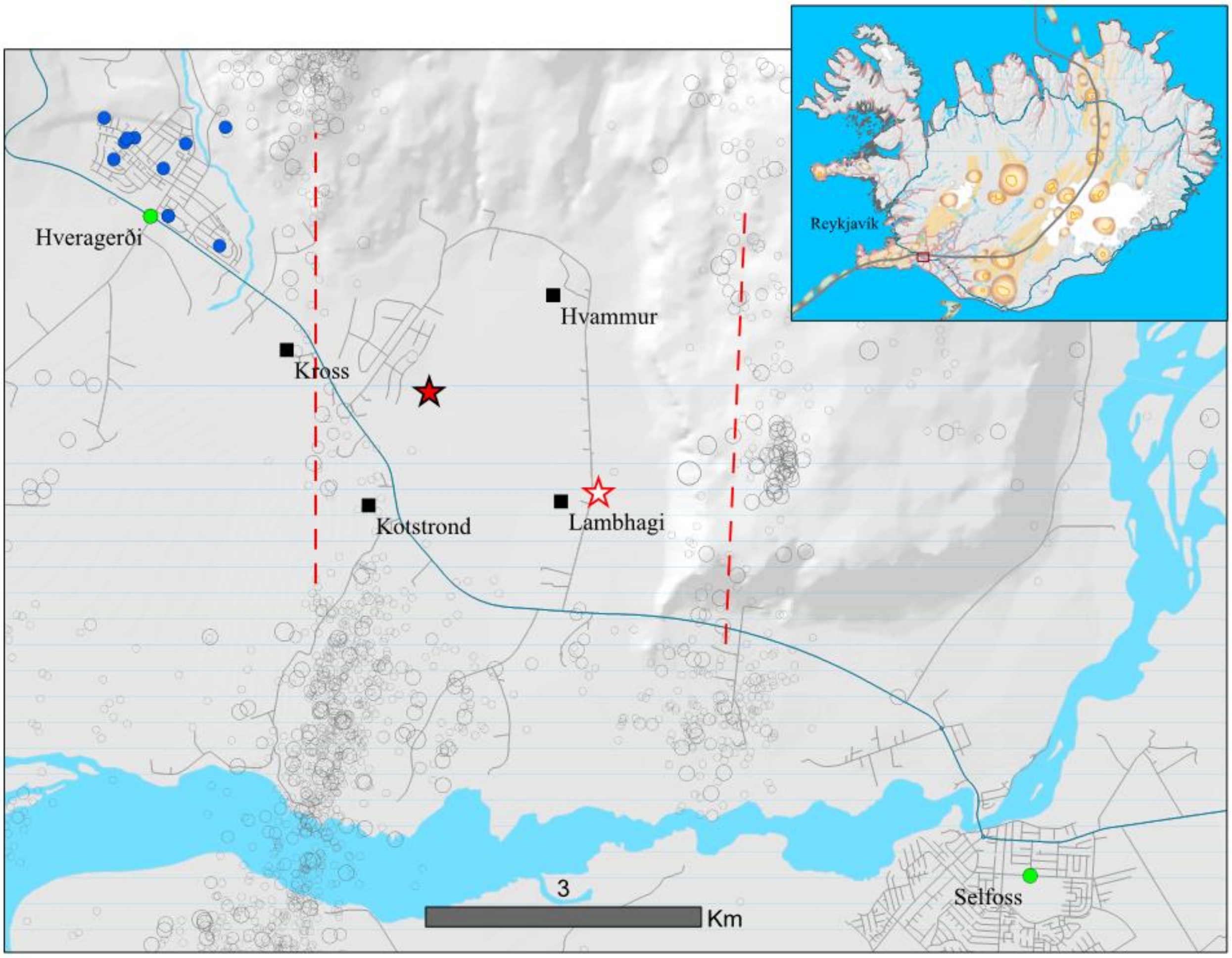

Fig. 1 – A map showing Hveragerði and its surroundings along with the macroseismic epicentre (solid red star) and the epicentre based on strong ground motion data (star near Lambhagi, see [5]) of the 29 May 2008 Mw 6.3 Ölfus Earthquake. Dashed red lines indicate the approximate locations of causative faults, the Ingólfsfjall Fault (east) and the Kross Fault (west). The hollow circles indicate the epicentres of earthquakes between 23 May to 31 June 2008. The blue dots in Hveragerði are the locations of strong-motion array stations that recorded the Ölfus Earthquake. The top-right inset shows the location of the study area, marked with a red rectangle, on a map of Iceland. The grey curve passing though the map is the Mid-Atlantic Ridge.

2.2 Ground motion in Hveragerði

The Ölfus Earthquake was recorded by 11 stations of the small-aperture strong-motion array (ICEARRAY, see Fig. 1). At these stations, 3-component ground acceleration time series were recorded. More details on the recorded ground-motion characteristics are presented in [6]. Peak resultant (of three components) ground acceleration recorded at the stations range from 51 to 101% of g (acceleration due to gravity). In terms of horizontal motion, rotation-invariant PGA (see, [7]) from 45 to 84% of g was recorded. Ground velocity and displacement time series at the 11 stations were obtained by a method described in [8]. Geometric mean horizontal PGV (geometric mean of two horizontal components) are in the range of 44cm/s to 65cm/s; rotation-invariant horizontal PGV are in the range of 48cm/s to 75cm/s, and resultant horizontal PGV are in the range of 65cm/s to 93cm/s. Strong velocity pulses due to forward directivity effects (see, for example, [9]) were observed in the ground-motion records. Rupakhety et al. [8] estimated that the stations experienced permanent displacement in the range of ~15-23 cm towards northwest during the earthquake. However, relative permanent displacement at nearby stations was not significant, and therefore, permanent displacement of the town (with insignificant relative motion at nearby points) is not expected to contribute significantly to pipeline damage. Also, no indication of a relative movement could be detected at the surface. Therefore, most of the damage to the pipes can be assumed to be due to wave propagation effects.

2.3 Buried pipelines in Hveragerði

Waste water system in Hveragerði consists of underground pipes with bell and spigot joints. Majority of the system consists of two separate pipes, i.e. sewage and drainage pipes to dispose waste water from private use and rain water, respectively. Only 2% of the pipelines serve the dual function of sewage and drainage disposal. The layout of the waste water pipe network in Hveragerði is shown in Fig. 2. The total length of pipes in the network is about 40 km. Most of the sewage and drainage pipes are laid in the same trench, with the drainage line about half a meter above the sewage line. The drainage line lies about 1.5-2.5m below the ground surface. All the pipelines are laid in straight lines between the manholes. The manholes for the sewage and the drainage line are usually located side by side at the same location.

Fig. 2 – Layout of the waste water pipes (shown in green) in Hveragerði.

The wastewater network in Hveragerði consists of segmented pipes with bell and spigot joints. About 95% of the pipe are made of unreinforced concrete (i.e. brittle pipes), and the rest are made of polyvinyl chloride (PVC) and Wavin X-Stream (SN).

Before the year 2000, concrete pipe manufacturing in Iceland went through major improvements. While oldest concrete pipe joints were sealed with hemp and cement-sand mortar, rubber rings were used later on. With the new manufacturing plants, rubber gaskets were installed in situ. In addition, quality of gravel used in the concrete mix was improved, and manholes were custom made. About 60% of the waste water system was constructed before the year 2000. About 90% of the concrete pipes have diameters of 150mm, 200mm, or 250mm; the size distribution is roughly uniform with each contributing about 30%.

3. Damage inspection and classification

After the 2008 Ölfus Earthquake, all the buried pipelines in the waste water systems in Hveragerði were inspected with a video camera which “travelled” through the pipelines. Video footage recorded by the camera was analysed in detail to investigate the type, extent, and location of the damages. This section presents an overview of the results obtained from such analyses.

3.1 Damage mechanism

The observed damages were classified into ten different categories (see, for example, [1]). The classification was based on the following considerations.

- Collapse of a part of a pipe due to extensive cracking is classified as category J (pipe collapse)
- Cracks/breaks at joints were classified as B (crushing of bell-spigot joints), C (blowout at tee), E (compression at tee), or G (pipe break at a manhole-pipe connection)
- Tensile failures at joints were classified as D (pull out at Tee) or F (pull out at bell-spigot joints)
- Longitudinal cracks/breaks anywhere along the pipes were classified as type H (longitudinal crack along pipe segment)
- Circular cracks in the pipes except those at T-connections were classified as type A (pipe segment circular crack)
- Other breaks/cracks in the pipes were classified as type I (pipe segment break)

Some examples of the damages sustained by the pipes in Hveragerði are shown in Fig. 3.

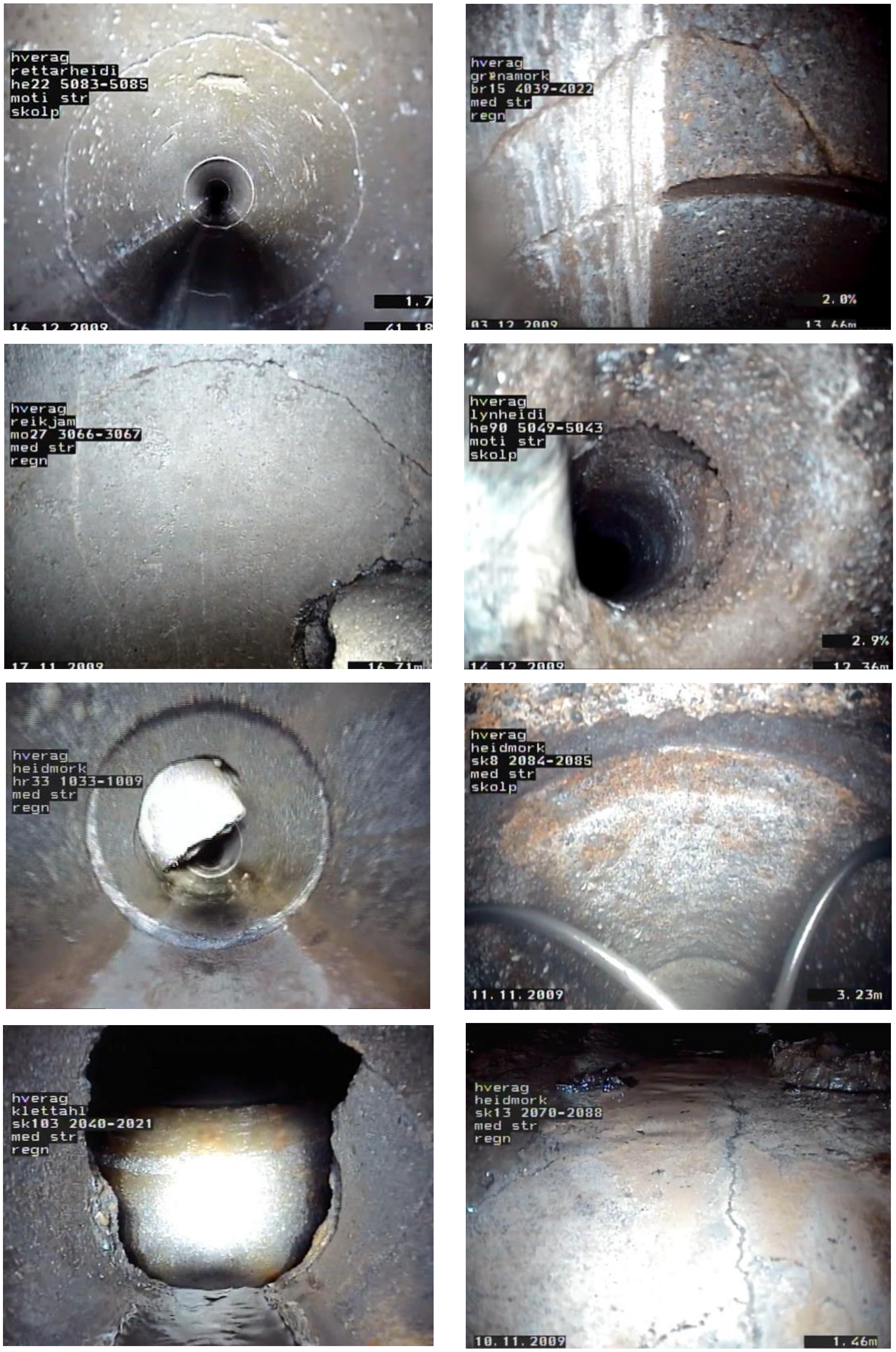

Fig. 3 – Some examples of the different types of damages sustained by the pipes in Hveragerði. The corresponding damage mechanisms are A to H, sequentially from top left to bottom right.

3.3 Damage states

To facilitate repair/restoration time and cost, HAZUS classifies repairs into two categories: breaks and leaks. A break is assumed to be more severe and harder to repair than a leak, implying longer repair time. In HAZUS, the standard proportion of breaks and leaks caused by wave propagation effects are assumed to be 20% and 80%, respectively. These proportions are interchanged when damages are caused by permanent ground deformation. In this study, the observed damage was classified into three different states of severity: minor, intermediate, and major. Cracks narrower than or equal to 2mm were classified as minor damage, those between 2mm and 5mm as intermediate damage, and those wider than 5mm as major damage. Tension/compression failures at pipe joints and pipe collapses were also classified as a major damage. Figure 6 shows the damage state distributions in the sewage and drainage pipeline. Both systems have similar damage state distribution, or about 1/3 damages in each damage state. Major damages were further classified into two categories: breaks and leaks. Breaks are defined as breakage and/or collapse of the pipe, and cracks wider than 5mm are defined as leaks. The relative proportions of breaks and leaks, were found to be comparable to what is suggested in HAZUS.

The distribution of different damage types in sewage and drainage pipes are shown in Fig. 4. Type A damage, which is pipe segment circular cracks, is found to be the most common damage mechanism. More than half of the damages are of this type. These damages are a result of flexural cracking induced by ground curvature. The distribution of damage types in sewage and drainage pipes seems to be similar, except damage type B, which is the crushing of bell and spigot joints, is less frequent in drainage pipes. The damage configurations for pipelines laid in 2000 and later are presented in Fig. 5. These pipes were fitted (in situ) with rubber gaskets at the bell-spigot joints and experienced significantly fewer joint-related failures than those constructed before the year 2000 in which the joints had been sealed with either hemp and cement-sand mortar or O-rubber rings. The distribution of different damage mechanisms in drainage and sewage systems was found to be similar, with type A being the most frequent damage mechanism.

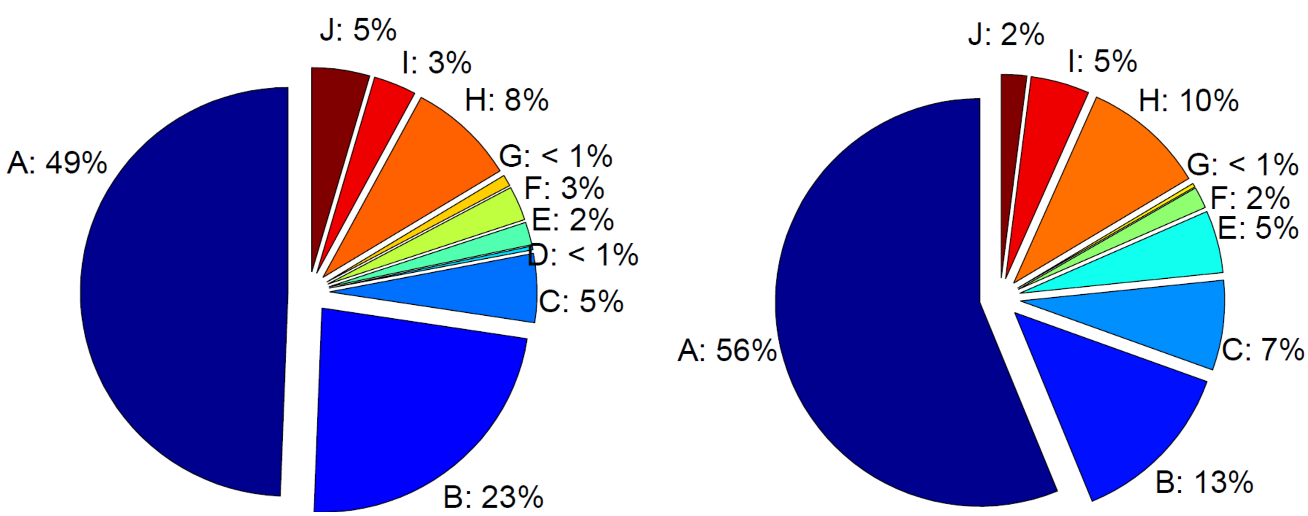

Fig. 4 – Distribution of damage types in sewage (left) and drainage (right) pipes.

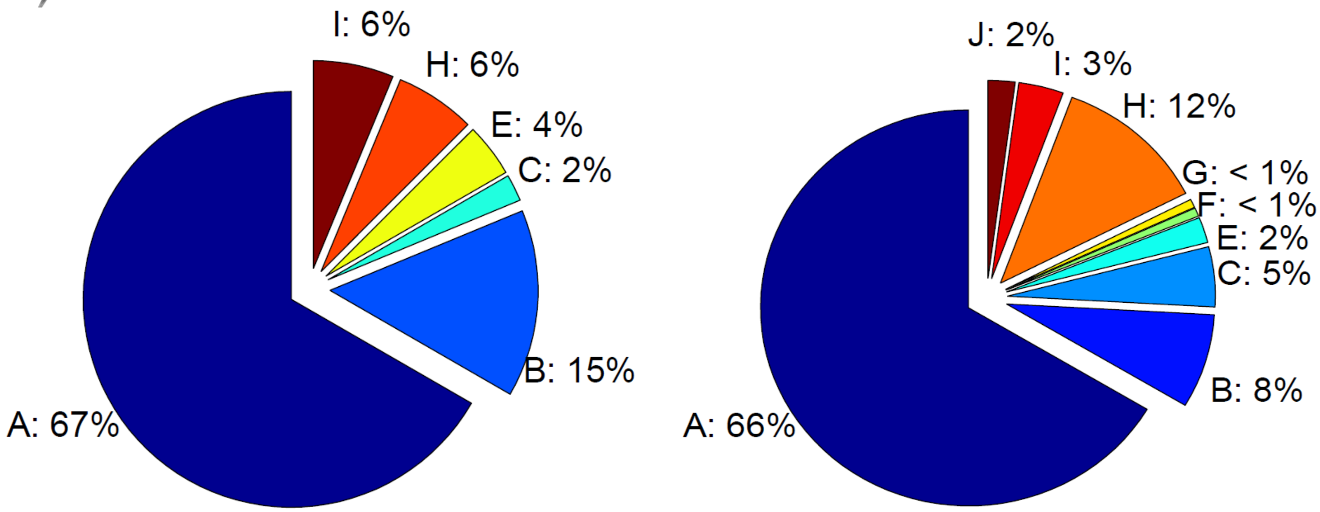

Fig. 5 – Damage distributions in the sewage (left) and drainage (right) pipes constructed in 2000 and later.

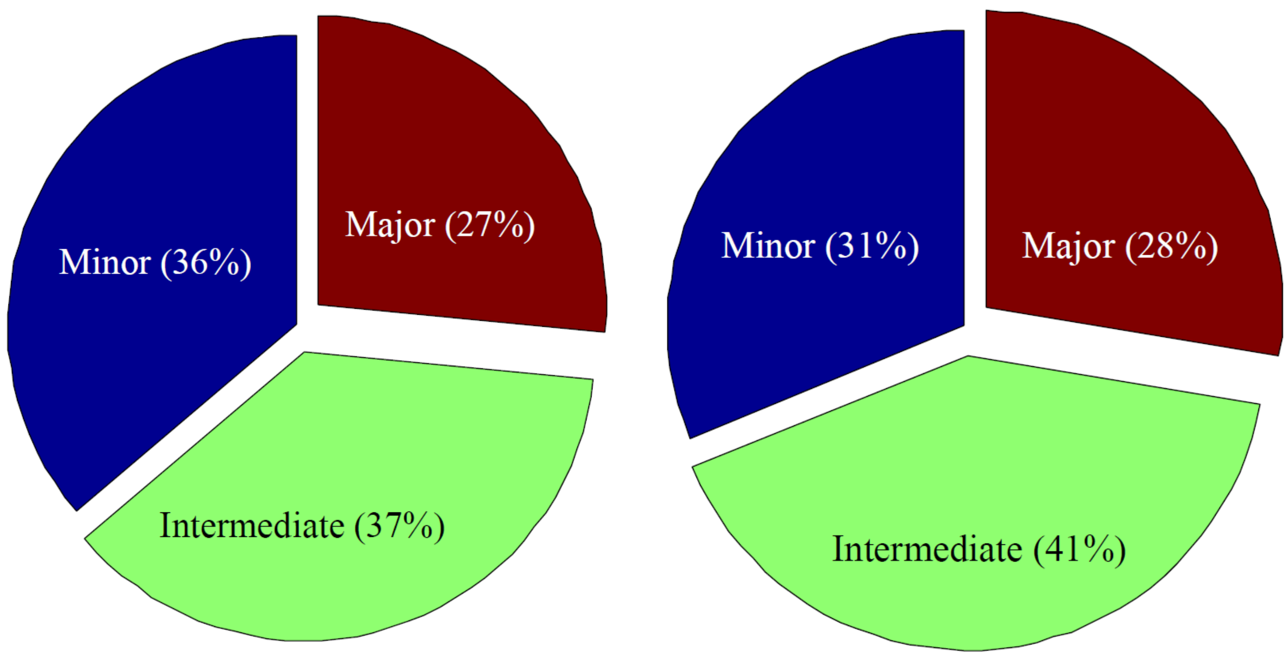

Fig. 6 – Damage states in sewage (left) and drainage(right) lines.

3.3 Comparison of damage in sewage and drainage pipes

It was observed that the damage rates in the sewage and drainage pipes were significantly different. The total lengths of the pipes performing these two functions are approximately the same. Figure 7 shows the number of damages per unit length (km) of sewage, drainage, and dual function pipelines.

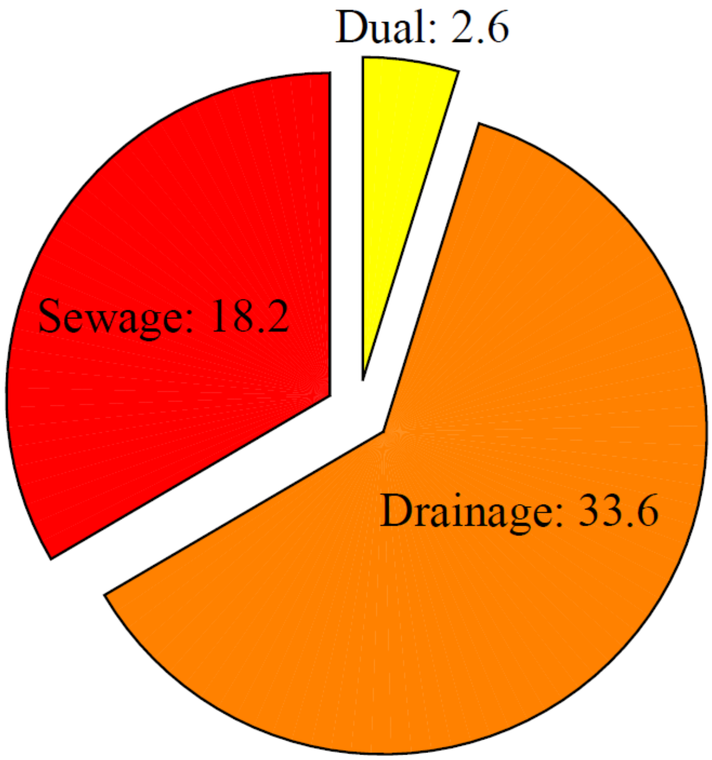

Fig. 7 – Comparison of damage ratios by pipe function; the numbers shown in the figure are number of damages per km of pipe.

4. Discussion and conclusions

A detailed analysis of the damages caused by a strong nearby earthquake on the underground pipes in Hveragerði was conducted using video footage collected by camera-mounted robots that travelled through the pipes after the May2008 Ölfus Earthquake. Damages were classified into 10 different mechanisms. It was observed that he most common mode of damage is due to circular cracks, i.e., damage type A. The next common mode of damage was crushing of bell and spigot joints. Frequency of this type of damage was found to be higher in joints sealed with either hemp and cement-sand mortar or O-rubber rings and lower in joints sealed with in-situ installed rubber gaskets. This confirms that seismic performance of underground pipes can be improved by using flexible rubber gaskets at the joints in place of brittle cement mortar. Depending on the severity, damages were classified into three categories: minor, intermediate, and major. It was observed that the frequency of these different categories were approximately the same.

A very interesting observation from the damage analysis is that the damage rate in sewage pipes is about 57% of that in the drainage pipes. The drainage pipes and sewage pipes are made of the same material and are of similar age. They are laid in the same trench, with drainage pipes lying only about 0.5m above the sewage pipeline, and therefore the significant differences in damage rates is not likely to be due to differences in ground motion experienced by these pipes. The sewage pipes lie almost on the engineering bedrock, while the drainage pipes are laid over backfill material. Some settlement of the backfill including potential interaction of the pipes with the surrounding soil may be the cause of higher damage rates in the drainage pipes. One notable difference between the drainage and the sewage pipes is that the sewage pipes are more restrained laterally than the drainage pipes. This restraint is provided by pipes and tees, at 10-20m intervals, connecting the main sewage pipes to the branches serving the houses. The extra stiffness provided by these lateral restraints might have caused lesser deformation (and damage) of the sewage pipes compared to the drainage pipes. Generally, damages tend to concentrate at or near connections and geometrical discontinuities (such as tees). However, this is not the case in the pipelines being studied here. Although the sewage pipes have much larger number of such discontinuities, they are found to suffer much less damage than the drainage pipes. The relative number of damages related to the tees were found to be similar in drainage and sewage pipes. Around the year 2000, concrete pipe manufacturing in Iceland underwent several improvements in terms of materials, compaction methods, and the joints used. These improvements led to the reduction in damage rates by almost 50%.

It was also observed that the damages in Hveragerði were much larger than what would be estimated from the commonly used fragility equations, such as those in ALA [10] and HAZUS [11]. For the smallest and largest PGV recorded in Hveragerði, the ALA fragility curves estimate, on the average, 0.1 and 0.17 repairs per kilometre (km) of pipeline length respectively, while the HAZUS fragility curves estimate 0.5 and 1.3 repairs per kilometre of the same. The upper bound number of repairs per km of pipe length estimated by ALA for the smallest and the largest PGV recorded in Hveragerði are about 0.3 and 0.5. In contrast, the pipelines in Hveragerði suffered 26 damages per km of their lengths. As the fragility functions in ALA and HAZUS are mostly based on only those damages that were reported to be repaired, and because many other damages might have gone unnoticed, it can be expected that these fragility functions are more representative of the most severe damages. The severe or major damages experienced by the pipes in Hveragerði was about 6,9 per km of their length. This damage rate is almost 6 times the largest damage rate estimated by the standard fragility functions. These observations indicate that the ALA and HAZUS fragility models for risk assessment of buried pipelines, like the ones being studied in this work, when subjected to strong ground motion in the epicentral are not reliable and could lead to serious under-estimation of potential risk. This is an important lesson for managing seismic risk to lifelines in the South Iceland lowland. In order to reduced damages to such systems and thereby minimize disruption after potential future earthquakes, more reliable fragility functions based on local data and experience are required. Such functions are being developed by the authors.

5. Acknowledgements

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