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Performance of sewer pipes with liner during earthquakes

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ABSTRACT

Recent earthquakes have shown that liquefaction and associated ground deformations are major geotechnical hazards to civil engineering infrastructures, such as pipelines. In particular, sewer pipes have been damaged in many areas in Christchurch as a result of liquefaction-induced lateral spreading near waterways and ground oscillation induced by seismic shaking. In this paper, the addition of a flexible AM liner as a potential countermeasure to increase sewer pipe capacity was investigated. Physical testing through 4-point loading test was undertaken to characterise material properties and the response of both unlined pipe and its lined counterpart. Next, numerical models were created using SAP2000 and ABAQUS to analyse buried pipeline response to transverse permanent ground displacement and to quantify, over a range of pipe segment lengths and soil parameters, the effectiveness of the AM liner in increasing displacement capacity. The numerical results suggest that the addition of the AM liner increases the deformation capacity of the unlined sewer pipe by as much as 50 times. The results confirmed that AM liner is an effective countermeasure for sewer pipes in liquefied ground not only in terms of increased deformation capacity but also the fact that AM-Liner can prevent influx of sand and water through broken pipes, making sewer pipes with liner remaining serviceable even under severe liquefaction condition.

Keywords: liquefaction, ground displacement, pipelines, liner, physical test, numerical simulation

1 INTRODUCTION

The September 2010 and February 2011 earthquakes in Christchurch have shown that liquefaction and associated ground deformations are major geotechnical hazards to engineering infrastructures, such as pipelines, during earthquakes. In particular, sewer pipes have been damaged in many areas in Christchurch as a result of liquefaction-induced lateral spreading near waterways and ground oscillation induced by seismic shaking. Although most of the damaged sewer and water pipes in Christchurch were in sections made of asbestos cement (AC), several segments of polyvinyl chloride (PVC), concrete and polyethylene (PE) pipes were also sheared, pulled out or compressed at various levels, and these damages affected the function of the sewer network in many places (Giovinazzi & Wilson 2012). An example of a typical damage observed to sewer pipe is shown in Figure 1(a).

Conventionally, pipe re-lining has been used to rehabilitate cracked or damaged portions of pipes as a means of completely trenchless form of restoration. Polymeric linings are remotely inserted in the pipes and the new composite layer provides secure continuity of pipe flow. The refurbished pipe generally has increased service life and enhanced hydraulic properties; however, the liners performance as countermeasure to earthquake-proof sewer pipes has never been established.

This paper presents the results of the investigation conducted to examine the performance of sewer pipes with AM liner during earthquakes and establish its performance as structural retrofitting measure to earthquake-proof sewer pipes. AM-Liner II is a PVC fold-and-form, thermoplastic, seamless liner conventionally used for trenchless rehabilitation of pipes 150 - 300mm in diameter (see Figure 1b). The liner is heated, pulled into the host pipe and re-formed with steam and air. As a result, a seamless, chemically-resistant PVC pipe is formed tightly to the interior of the existing host pipe. With

(a) *(b)*

Figure 1. (a) Example of damaged sewer pipe as a result of 2011 Christchurch Earthquake (ProjectMax 2012); (b) Coil of AM-Liner (American Pipe & Plastics Inc 2005)

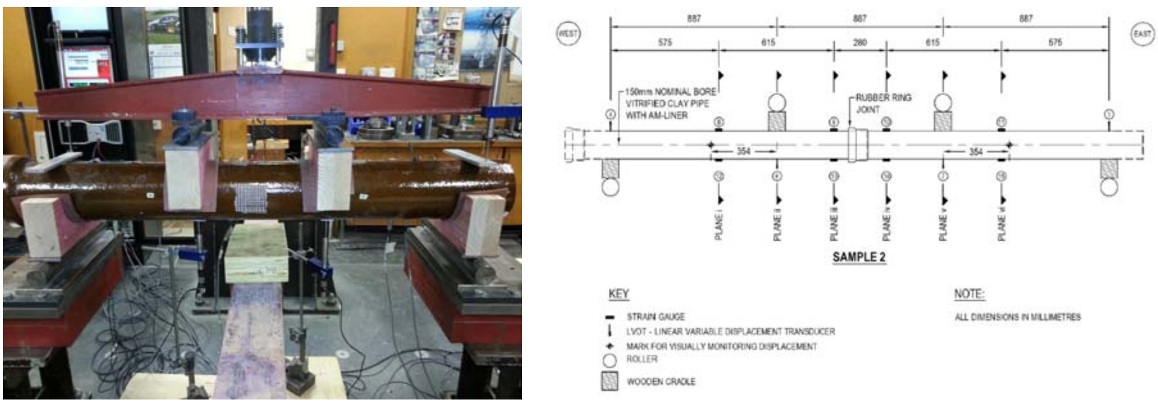
its smooth seamless interior, the reduced friction loss more than compensates for the internal diameter change. It is an environmentally friendly way to rehabilitate damaged pipes, negating the need for costly and time consuming excavation (PipeTech 2012).

For this purpose, physical model tests were conducted on lined and unlined sewer pipe segments using 4-point loading apparatus. The observations were then used to numerically simulate the response of lined and unlined sewer pipes when subjected to liquefaction-induced lateral spreading through parametric analyses. From the results obtained, more comprehensive performance criteria were then formulated for the specified pipe and ground conditions.

2 METHODOLOGY

2.1 Physical model tests

Firstly, physical model tests were conducted to investigate the performance of sewer pipes equipped with AM-liner when subjected to transverse loads. For this purpose, four-point loading tests were performed on two specimens of 150mm nominal bore vitrified clay pipe with an average wall thickness of 20mm. Sample 1 was a single section of unlined vitrified clay pipe which was approximately 1.5m in length. On the other hand, Sample 2 was made up of two sections of vitrified clay pipe joined together and continuously lined by the AM-liner. The joint was sealed using a rubber gasket. The outside diameter of the AM-liner was practically the same as the inside diameter of the host pipe. The AM-Liner had an average wall thickness of 5.87mm which results in the inside diameter of the AM-liner being 138.26mm. All the pipes used had a standard socket and spigot ends.



(a) *(b)*

Figure 2. (a) Test set-up for the 4-point load test (Sample 1); and (b) location of sensors (Sample 2).

For the four-point load test, the pipe surface was first prepared by sand blasting and de-greasing to provide a good bonding surface for the strain gauges which were installed at pre-defined locations. The pipe specimen was then placed on wooden cradles which rested on the support stands of the MTS test machine. A thin rubber material was placed between the pipe and wooden cradle to prevent line failure along support sections.

The centre of the pipe was approximately aligned below the force actuator of the MTS, with the load spreaders adjusted so that all four supports were at the middle-thirds of the pipe length (see Figure 2a). Linear variable displacement transducers (LVDT) were also installed at pre-defined locations (see Figure 2b). All sensors were connected to the data acquisition control unit. The downward deflection was applied at a controlled rate, and the test was stopped when the maximum deflection limit of 300mm was reached or when the pipe or AM-liner had completely failed, whichever came first. Video recording with grid references were also used for visual representation of the pipe deflection.

2.2 Numerical analyses

To simulate the response of the pipes both in the model tests as well as to liquefaction-induced permanent ground displacements (PGD) (see Figures 3a and 3b), numerical analysis was performed using the computer program SAP2000 and ABAQUS. SAP2000 is a software package for structural analysis of linear and nonlinear problems and is capable of conducting static and dynamic analysis. Nonlinear pushover static analysis was used to analyse the pipe and liner and made use of material nonlinearity tools to address inelastic structural responses where the behaviour of the system deviates from the initial stiffness tangent characteristic of linear-elastic behaviour. The inelastic behaviour of the material is represented using a monotonic curve (or backbone curve) whose characteristics are based on moment-curvature relationships for the structure (CSI 2008). The numerical model used in SAP2000 is shown in Figure 3(c).

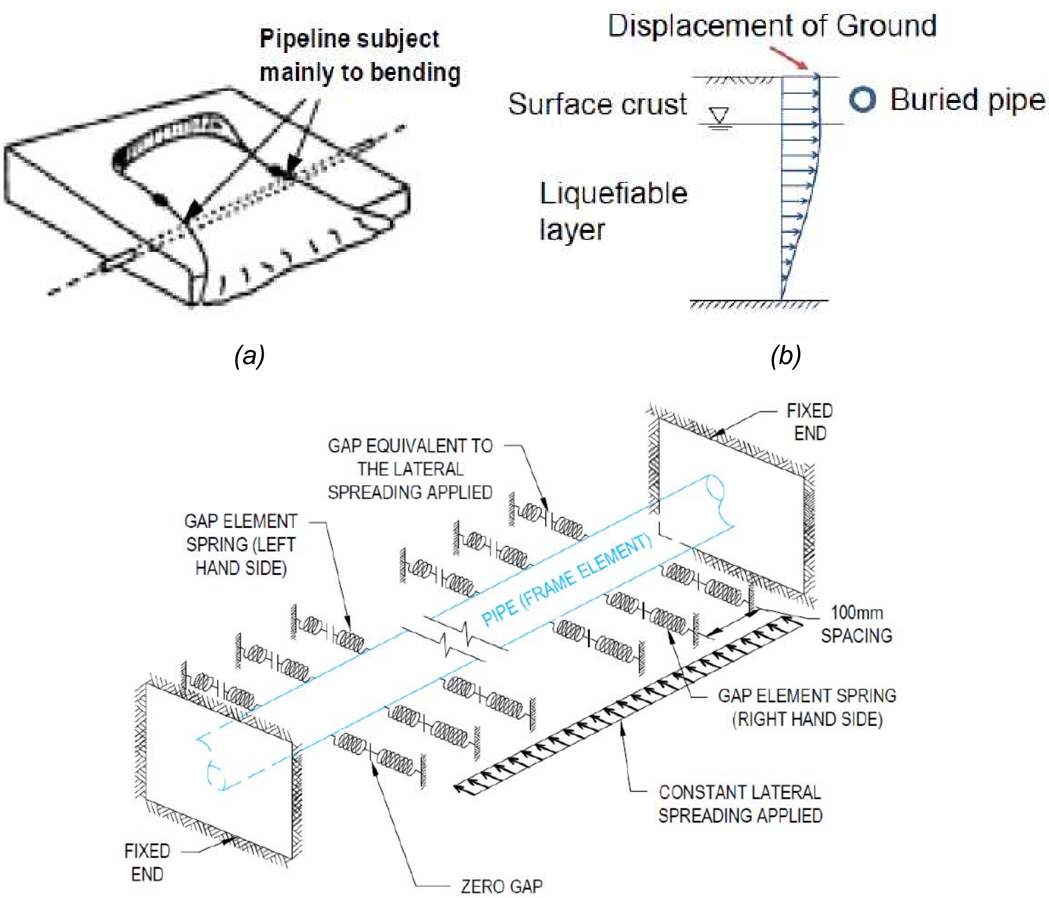
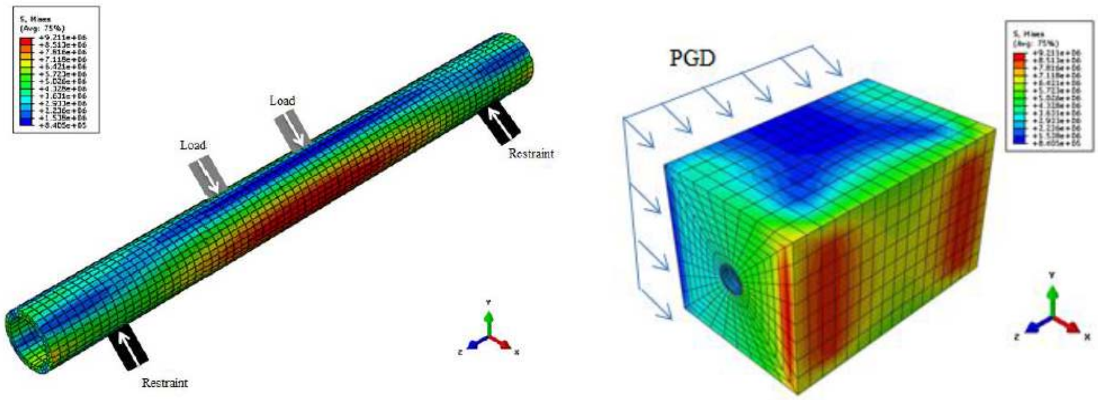


Figure 3. (a) Schematic diagram of pipeline subjected to transverse lateral spreading; (b) location of pipeline in laterally-spreading liquefied ground; and (c) numerical model for SAP2000 analysis.



(a) *(b)*

Figure 4. Model in ABAQUS: (a) computer model of the 4-point load test; and (b) model for the pipe subjected to lateral spreading.

To supplement the results, a 3-D finite element (FE) model was created in ABAQUS (version 6.12-3) with the intention of replicating a buried pipeline subjected to transverse PGD. The numerical modelling was aimed at exploring the possible increase in capacity with the addition of the AM liner. Figure 4(a) shows the replica of the ABAQUS model for the physical model test with 4-point loading, while the numerical model for the buried pipe under transverse PGD (vis-à-vis Figure 3b) is depicted in Figure 4(b).

3 RESULTS AND ANALYSES

3.1 Physical model tests

In four-point loading tests, the bending moment is constant over the outer sections of the pipe (i.e. between the ends and the loads); this type of loading provides a way not only to characterise the material properties of the unlined pipe and its AM-lined counterpart, such as the Young's Modulus (E) and yield strain (ε_y), but also to have a better idea (in terms of modelling) on the interaction between the pipe and the liner and their overall response as composite structure.

3.1.1 Unlined pipe

As expected, the loading test on the unlined vitrified clay pipe showed an initial elastic response; the records from the strain gauges showed that the stress-strain curve prior to yielding indicate an elastic modulus of E = 56 GPa, approximately 12% higher than the manufacturer's quoted value of 50 GPa. There was no plastic behaviour observed; in fact a brittle failure occurred when the mid-span displacement was about 6 mm, representing a strain ε_y = 0.02% at the outer ends.

3.1.2 AM-lined pipe

The relationship between the displacement (as monitored by the LVDTs) and resistance provided by the AM-lined pipe is shown in Figure 5. It is clear that during the initial stage of loading, the response is elastic; recordings from strain gauges indicate an equivalent modulus of E=66.7 GPa. With further loading, some cracks occurred mostly at the spigot and socket joints. However, longitudinal cracks developed at the top and bottom of the pipe when the force was about 3 kN, which resulted in a small drop in the resistance. With further application of the load, the elastic response continued until another crack developed and the force dropped. Each drop in the force-displacement relation actually indicated formation of large crack. The test was terminated when the displacement at the centre was 268 mm; at this point, the resistance dropped to 0.93KN.

Taking a closer look at the force-displacement curve, three regions can be observed. The first can be called the "pipe-dominant region" where the pipe mostly failed as shown by random cracks. With further loading, the liner started to become effective and the "composite region" was mobilised; at this

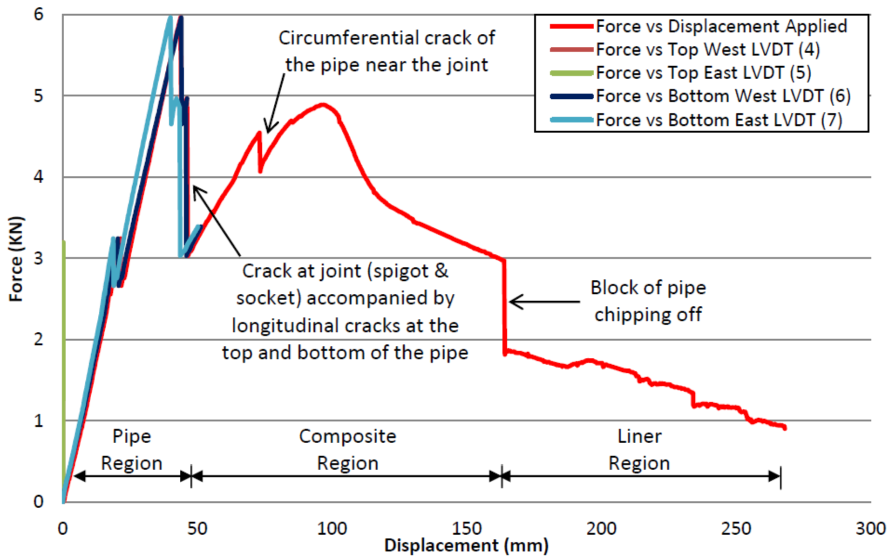


Figure 5. Force-displacement curve for the AM-lined pipe subjected to 4-point loading.

region, only a few cracks were noticed. The curve in this region is smoother as would be expected for a ductile material, indicating that the AM-liner was absorbing some of the strains as it elongated. Once the pipe became totally ineffective, the third zone is mobilised, called "liner region" where only the AM-liner was absorbing the load. Note that there was no abrupt drop in resistance in this region, showing that the AM-liner was getting displaced and buckled as the load was being applied. When the test was terminated, the elongated AM-liner had completely collapsed, closing the space for possible wastewater flow. The before and after test photos are shown in Figure 6. Based on these results, it can be concluded that the AM-liner aids in maintaining the serviceability of the pipe during four-point bending test.

It should be mentioned that the quality of results may have been compromised due to debonding of the AM-liner from the pipe walls. During testing, the AM-liner had slipped with respect to the pipe wall by about 80mm.This would have also decreased the amount of strain experienced by the AM-liner and it may have failed earlier if debonding had not occurred.

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(a) (b)

Figure 6. Photos of load test for AM-lined sewer pipe: (a) before the test; and (b) after the test

3.2 Numerical analyses

3.2.1. Physical test validation

As discussed above, on testing the AM-lined pipe, once yielding of the vitrified clay pipe had occurred, the stress was transferred to the liner. The AM liner was able to sustain deformation so large that it reached the capacity of the testing machine before yielding of the liner was observed. For the purpose of numerical modelling, the transfer of the strain to the AM-liner on yielding of the pipe was simplified; the drop in stress when the host pipe yielded (formation of cracks) and the AM-liner taking over is illustrated in Figure 7. With this approach, the pipe and the AM-liner were not treated as independent structure, but rather as composite one; hence, possible slippage of the liner was not considered. The moduli recorded in the tests were used to represent the response of the composite section and liner.

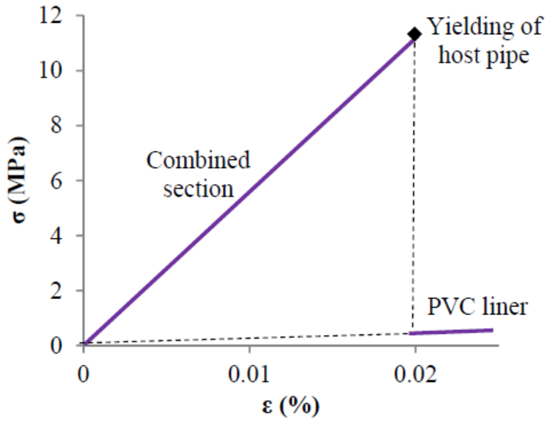


Figure 7. Simplified stress-strain relation for the vitrified clay pipe with AM-liner.

For the purpose of validating the 4-point loading test for use in the succeeding simulation, ABAQUS was used initially with the numerical model shown in Figure 4(a). The pipe consisted of a solid extrude and used an elastic modulus of 56 GPa for the unlined one and 66.7 GPa for the lined one as established through physical testing. Its geometry resembled the unlined test specimen, 1.6 m in length with an ID of 150 mm and wall thickness of 20 mm. When analysing the lined pipe, the thickness was changed to consider the effect of the AM-liner.

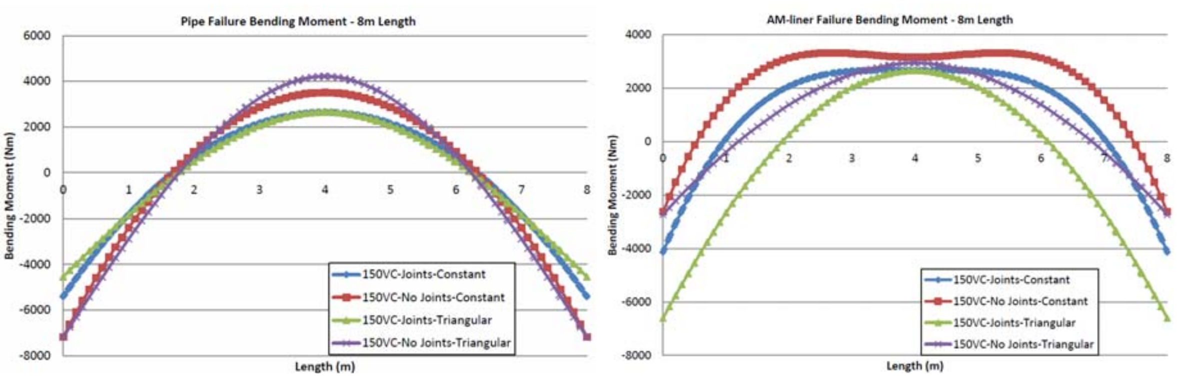
The results of the simulation for both tests on lined and unlined pipes showed good agreement with the tests at small strain levels. Comparison of recorded strains (as recorded by gauges) and those calculated by ABAQUS at various stages of loading indicated good correlations; however, once the host pipe in Sample 2 yielded and cracked, the simulation was not as good because the model did not capture the slippage on the AM-liner inside the pipe as well as the progressive formation of cracks, which affected the transfer of stresses from the host pipe to the AM-liner. Nevertheless, the stress-strain relation of the composite pipe appeared to represent the overall behaviour after yielding of the host pipe.

3.2.2. Simulation of pipe subjected to transverse lateral spreading

Next, the response of both lined and unlined pipes under transverse lateral spreading due to soil liquefaction is investigated. The schematic diagrams of the scenario investigated are shown in Figures 3(a) and 3(b). Initially, the nonlinear static pushover tool in SAP2000 software was used to examine the moment-curvature capacity of the pipes. Both constant amplitude and triangular profiles of lateral spreading displacement was considered to act on pipes with different lengths (L=8, 16m) exposed to the movement. Both continuous and segmented pipes (with joints) were considered. The soil springs were assumed to have linear elastic stiffness and were calculated based on correlation with Standard Penetration Test (SPT) blow count value, as proposed by the Architectural Institute of Japan (2001). For the purpose of the analysis, $(N_1)_{60}$=5 and 10 were considered, as these values represent surface ground conditions near Avon River in Christchurch, where many sewer pipes were damaged.

The bending moment at pipe failure for 8m pipe length is shown in Figure 8(a). When the pipe was modelled as a continuous pipe, the pipe failed at the fixed ends when bending moment capacity was reached. For pipes with joints, the central pipe joint located at the centre of the pipe length failed first. Pipes with joints required less shear force and bending moment to reach failure point than those with no joints. The profile of the PGD applied did not have much influence on the location of failure points along the pipe length, but it mostly influenced the magnitude of lateral displacement at which the pipe or AM-liner failed.

After the pipe had failed, further lateral spreading was applied until the AM-liner reached its ultimate moment capacity. The bending moment at AM-liner failure for 8m pipe length is shown in Figure 8(b). As was the case earlier, for continuous pipes, the AM-liner failed at the fixed ends and for segmented pipes with joints, the AM-liner failed at the central joint. The flattening of bending moment at the centre of the figure is due to the closure of gaps in left side springs (see Figure 3c). When the gaps close, the spring stiffens and tries to resist any further displacement. This reaction was expected by the left side gap element springs. When lateral spreading ceases, the pipeline would try to continue deforming in a parabolic shape. This attempt to deform as a parabola would be resisted by the surrounding soil. The shape of bending moment diagram depends on several factors, such as the pipe length, the location of initial pipe failure, the amount of lateral displacement applied, the gap in the left hand springs, and the location of joints, to mention some. Similar trend was observed for the L=16m long model.



(a) (b)

Figure 8. Bending moment distribtution of the 8m long pipe: (a) at failure for the unlined pipe; and (b) at failure for the lined pipe.

To summarise, the following was observed regarding the initial failure location in majority of the scenarios modelled: (1) for continuous pipes, the pipe and AM-liner failed at the ends while for segmented pipes, most failures were at the central joint; and (2) The lateral spreading profile did not have much influence on the location of failure points. A summary of the results for the case of SPT $(N_1)_{60}$=5 are shown in Table 1.

Table 1: Results of SAP2000 pushover analysis

Pipe Length (m)	PGD Profile	Scenario	Magnitude of displacement applied (mm)	
			No Joints	With Joints
8	Constant	When pipe failed	46	35
		When liner failed	117	95
	Triangular	When pipe failed	71	45
		When liner failed	175	115
16	Constant	When pipe failed	25	12
		When liner failed	141	147
	Triangular	When pipe failed	45	20
		When liner failed	280	201

Segmented pipelines generally had the pipe and AM-liner failed at a lower lateral displacement than continuous pipelines; on average, the latter had 67% more displacement capacity than segmented pipes. Pipelines subjected to constant PGD profile failed at a lower lateral displacement than pipelines subjected to triangular PGD profile. Pipelines subjected to triangular PGD profile required 1.2 to 2 times more lateral displacement to reach failure point when compared with constant PGD profile. When the lengths of pipelines were compared, it was observed that AM-liners in longer pipelines maintain higher serviceability. This implies that longer AM-liners will have higher lateral displacement capacity. 16m AM-lined segmented pipeline subjected to triangular PGD profile had the highest increase in tolerance to lateral displacement, with the AM-liner increasing the displacement capacity by more than 900%.

ABAQUS was also employed to analyse the response of buried lined and unlined pipes subjected to transverse lateral spreading. The model is shown in Figure 4(b). Based on the model tests, the yield stress (σ_y) was taken as 11.25 MPa for the host pipe and 28 MPa for the AM-liner. The deformations required to reach these yield conditions are shown Table 2, for different lengths of pipe segment. Also shown, are the magnitudes of the PGD able to be withstood by unlined pipes, for comparison. The results are based on constant PGD profile, and SPT N-value $(N_1)_{60}$=5. It can be increased that the capacity of the unlined pipe is increased by more than 50 times with the installation of the AM-liner.

Table 2: Results of ABAQUS simulation (constant PGD profile)

Segment Length (m)	Scenario	Magnitude of displacement applied (mm)
1.6	When pipe failed	2
	When liner failed	101
2.0	When pipe failed	2.5
	When liner failed	120
2.5	When pipe failed	3
	When liner failed	137

4 CONCLUSIONS

Physical model tests and numerical simulation using SAP2000 and ABAQUS were conducted to examine the performance of vitrified clay sewer pipe with AM-liner. The major conclusions obtained are as follows:

- Four-point loading tests performed on unlined sewer pipe showed brittle behaviour and minimum deformation capacity. However, with AM-liner, the overall behaviour of the composite pipe showed ductile response, with the AM-liner taking over the strain when the host pipe cracked and yielded, resulting in larger deformation capacity.
- SAP2000 pushover analyses indicated that segmented pipelines generally had the pipe and AM-liner fail at a lower lateral displacement than continuous pipelines. Continuous pipes, on average, had 67% more displacement capacity than segmented pipes.
- Pipelines subjected to constant lateral spreading profile failed at a lower lateral displacement than pipelines subjected to triangular profile. When the lengths of pipelines were compared, it was observed that AM-liners in longer pipelines maintain higher serviceability. This implies that longer AM-lined pipelines will have higher lateral displacement capacity.
- ABAQUS 3D analysis confirmed the pipe with AM-liner performed better than unlined pipe under the same magnitude of PGD, geometry and soil conditions. The liner was still serviceable after the failure of the vitrified clay pipe, with the AM-lined pipe having 50 times the deformation capacity of the unlined one.

Thus, these results confirmed that AM liner is an effective countermeasure which can increase the deformation capacity of sewer pipes in liquefied ground. Moreover, during liquefaction, AM-Liner can prevent influx of sand and water through broken pipes and the pipes can remain serviceable. As a result, restoration of damaged sewer pipes can be delayed and, instead, much needed attention can be provided to more important services or facilities.

5 ACKNOWLEDGEMENTS

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