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The Chemical and Structural Analysis of Pipeline Repair Materials

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Abstract

The integrity of a pipeline is essential in the proper functionality and prevention of catastrophic events such as explosions. Loss of integrity can lead to leaks or cracks which have the potential to affect operating temperature, pressure, and flow within the pipe. Pipe failure can be the result of corrosion, improper welded joints, and environmental stressors. Environmental factors such as flooding, earthquakes, and soil movement can all lead to damaged pipelines[1]. Previous studies such as the one conducted by Hanis Arifin et al., focused on improving the performance of the repair system for damaged pipes[2]. While repair materials of damaged pipelines are selected based on their ability to improve integrity, more research should be focused on repair materials that also prevent corrosion and act against environmental stressors. The goal of this paper is to study the current technology and present the repair materials that will prevent corrosion and enhance the integrity of pipelines. This study will review and identify effective repair materials by analyzing the chemical components, structural characteristics, and the use of simulation software to determine the maximum stress and pressure values in repaired pipes through existing literature.

Introduction

When discussing effective repair materials, it is important to consider what is causing the structural damage, the type of damage, how to prevent and/or repair the damage, downtime, and costs. Previous studies have focused on the investigation of soil movement as a common problem for damaged pipelines. Seismic events are known to cause pipeline displacement and liquefaction of the soil surrounding the pipeline. The liquefaction in the soil decreases the soil's shear strength leading to lateral deformations around the pipe. Cavities can form below the pipe which can quickly fill with the weakened soil deposits. The pipeline continues to lift from the soil with each subsequent earthquake, but at a lower rate for each subsequent earthquake[3].

Understanding the source of the problem for damaged pipelines is just as critical as understanding the various methods available to prevent future damage. Previous studies have focused on the stress distribution of a composite wrapper composed of reinforced putty examined as a repair method. The composite wrapper is typically a repair method applied to steel pipes used for oil and gas. Structural failure may be due to natural phenomena, as previously mentioned, corrosion, material or construction defects. Corrosion can affect structural integrity by decreasing the pipe wall thickness.

Finally, repair down time and costs can be fundamental in deciding on the best repair method. In a study conducted by R. Moeini et al., trenchless and open cut technology for wastewater pipelines was investigated as a means to reduce repair costs. The researchers also aimed to decrease the amount of time required to repair the damaged wastewater pipelines. Repair of wastewater pipelines may involve plugging the upstream end of the pipeline and pumping the wastewater into to the downstream end, resulting in a longer process repair time. Various natural phenomena contribute to damaged pipelines such as flooding or earthquakes. A common trenchless method known as "cured in place pipe" (CIPP) can cause a backup and overflow of wastewater into streets or homes in close proximity to the damaged pipes[1].

Method

To identify the possible source of structural integrity and its effects, shaking tables were used to model seismic activity responsible for soil liquefaction[3]. Pipelines of various weights underwent shaking table tests to analyze the type of displacement, the magnitude of displacement and uplift rate. Soil boxes consisting of steel frames and transparent acrylic walls were placed on top of the shaking tables. Sand was placed in the soil boxes and the bottom layers of the soil were soaked with water. PVC pipes capped at each end, to prevent the intrusion of water or soil, were used to model the pipelines. Filling material was placed inside of the PVC pipe to model various weights of the pipelines. For the three different weights, three tests were run: TP, TP_1, and TP_2. Each test is defined by a different apparent unit weight, initial saturated sand unit weight, and initial soil relative density. The characteristics for each test can be seen below in Table 1.

Table 1 – Test Characteristics

Test ID	Pipe apparent unit weight* (kN/m^3)	Initial saturated sand unit weight (kN/m^3)	Initial soil relative density (%)
TP	6.8	18.62	50
TP_1	13.2	18.43	50
TP_2	20.7	18.65	50

*The apparent unit weight is computed as the total weight of the pipe (including the filling material) divided by the pipeline volume

The pipe was placed 25 cm from the ground level of the soil box. The pipe displacements were measured using laser sensors attached to a vertical steel frame connected to the pipe. In addition to the laser sensors, accelerometers and pore water pressure transducers were also used. The same shaking sequence was used for each run, however the weight of the pipeline and soil relative density were changed. An image of the simulation can be seen in Figure 1.

Figure 1 – Shaking Table model

The first technique considered was the composite repair method. This technique used to prevent structural failure involved the application of reinforced putty. The putty was reinforced with nanoparticles known as carbon nanotubes that would allow for the putty to act as an additional layer of protection. This would, in turn, reduce the layers of composite wrapper required and improve the load bearing capacity.

To model the simulation, ABAQUS v6.14 finite element analysis software was used to make predictions for failure pressure as well as stress and strain values. Hexahedral meshing and solid C3D8R elements were used to model the steel pipe and putty. As for the dimensions, 168.3 mm was used for the outer diameter, 7.11 mm for the thickness and 1200 mm for the length. A four-node shell element (S4R) was used to model the composite wrapper. The pipe was also modeled to represent a corrosion defect in the center of the pipe using 2D rectangular geometry. The defected area was represented by an arc length of 100 mm and a depth of 3.555 mm. The putty was also modeled to cover the size of the defect area. The model of both the steel pipe and defected steel pipe with repaired composite wrapper can be seen in Figure 2.

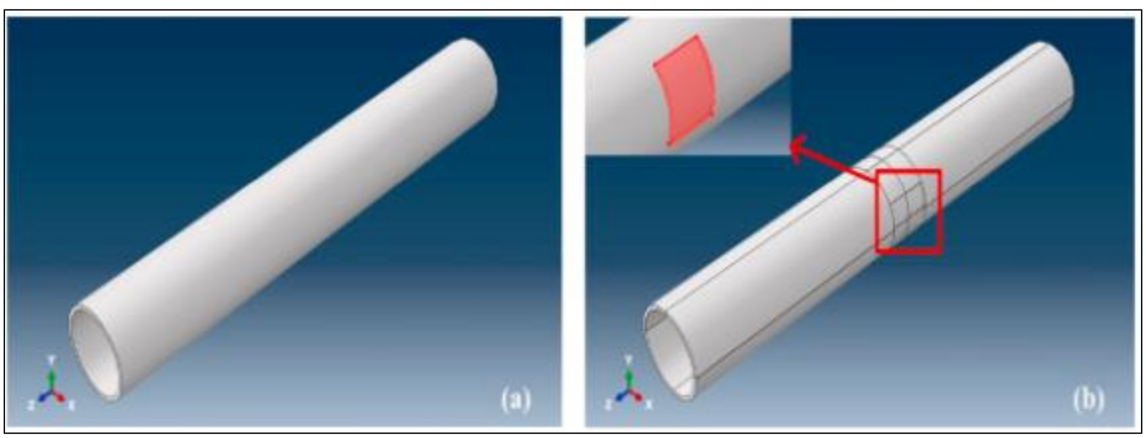

Figure 2 – ABAQUS model of (a) steel pipe without defect (b) pipe with defect and composite wrapper

Additional properties and their values that were input into ABAQUS to model the steel pipe, putty and composite wrapper can be seen below in Table 2 and Table 3**.** The steel pipe and the putty were modelled in separate layers and the end caps of the pipe were simulated by restricting the end nodes of the pipe. The putty was composed of Bisphenol A diglycidyl ether, aliphatic amine hardener, and 0.5 wt% carbon nanotubes (CNTs). The composite wrapper itself was composed of E-glass fiber infused with an epoxy resin. While the details about the mesh were not provided, it should be noted that a thinner mesh was applied to the area repaired with the composite wrapper. A nonlinear analysis was performed in ABAQUS to analyze failure pressure.

Table 2 – Material properties of steel pipe and putty if ABAQUS model

Material	**Properties**	**Value**
Steel Pipe	Yield Strength **(MPa)**	293.27
	Ultimate Tensile Strength **(MPa)**	480.13
	Young's Modulus **(GPa)**	221.37
	Poisson Ration	0.3
	Density **(kg/m^3)**	7850
Putty	**Grout A (Neat Putty)**	
	Ultimate Tensile Strength **(MPa)**	26.42
	Young's Modulus **(GPa)**	2.21
	Grout B (Reinforced Putty)	
	Ultimate Tensile Strength **(MPa)**	40.51
	Young's Modulus **(GPa)**	2.33

Table 3 – Material properties of composite wrapper

Parameter (unit)		**Value**
Density **(kg/m^3)**		1659.20
Ultimate Tensile Stress **(MPa)**	*Hoop*	241.27
	Axial	169.43
Ultimate Compression Stress **(MPa)**	*Hoop*	55.55
	Axial	80.78
Young's Modulus **(GPa)**	E_1	14.32
	E_2	10.10
	E_3	5.50
Poisson's Ration	v_{12}	0.11
	v_{13}	0.43
	v_{23}	0.43
Shear Modulus **(GPa)**	G_{12}	3.28
	G_{13}	1.64
	G_{23}	1.64

In an effort to not only cut down on repair time of damaged pipelines, but also reduce costs, the method used by Moeini et al. involved the water bypass system previously mentioned; plugging the upstream end of the pipeline. The water is allowed to collect upstream and in manholes until it reaches its max capacity, which in turn, determines how long the water is pumped. The water capacity is dependent upon pipe length, pipe diameter, the age of the pipe and flow capacity to name a few. The type of plug and packer used depends on the maximum tolerable pressure. The maximum tolerable pressure, pumping rate were calculated using the model. The piping diameter was taken into consideration and reduced until there was no longer any backflow. The adjusted piping diameter allowed for the capacity to be modified, thus reducing the pumping discharge by 70%.

To model the simulation, Bentley SewerGEMS V8i software was used to analyze the minimum pumping method. The software allowed for the wastewater collection networks to be designed under specific conditions for gravity flow and pressure. SewerGEMS also allowed for data visualization from model simulations in the form of tables and figures. The data was based on and compared to that of two previous case studies on wastewater collection networks. The first case study, based in Isfahan, Iran, consisted of a smaller network of 38 polyethylene pipes with a diameter of 800 mm. The second case study, which focused on the city of Ardekan, centered on the larger network of 111 polyethylene pipes. The model of the first case study was simulated under steady state conditions, while the second case study was simulated under non-steady state conditions. The non-steady state condition allowed studying the effects of the repair time.

Results & Discussion

While the soil model results were performed on a smaller scale than that of an actual pipeline, the recorded responses provide insight into how seismic activity can affect structural integrity. It was found that the stiffness of the soil layers decreases as the pore water pressure increases. Deeper layers of the soil model were not as susceptible to liquefaction, as shown by the readings from the AC sensors. Pipe with a weight larger than that of the saturated weight of the sand experienced smaller upward displacement than smaller weighted pipes. A difference in initial soil relative density, 40% as compared to 50%, can also affect uplift. The 40% relative density caused a slight upward displacement. Pipes of larger weight also lead to higher horizontal displacements than their vertical displacements, however the dislocations were not permanent. Displacement and liquefaction of soil are dependent upon initial soil conditions such as water pressure and density as well as the weight of the pipe. Heavier pipes and looser soil, or a combination of the two, were found to cause more susceptibility to liquefaction and larger displacements, whether vertical or horizontal.

The investigation on putty reinforced with CNTs first confirmed that the FE model was able to be used as an effective evaluation tool. Recorded burst pressure results were below the 15% margin of error when compared to previous studies. The putty was found to have high tensile strength and played a major role in load transfer and load sharing. The reinforced putty minimized the chances of sudden rupture in a repaired pipe. Promising results were seen more in Grout B, specifically, which was used in Pipe-2. The putty in Grout B resisted higher deformation before failure due to its larger amounts of strength and stiffness. Pipe-1 resulted in sudden rupture during stress analysis as seen below in Figure 3. Overall, the findings showed that the enhancements in strength of the putty were due to the CNTs.

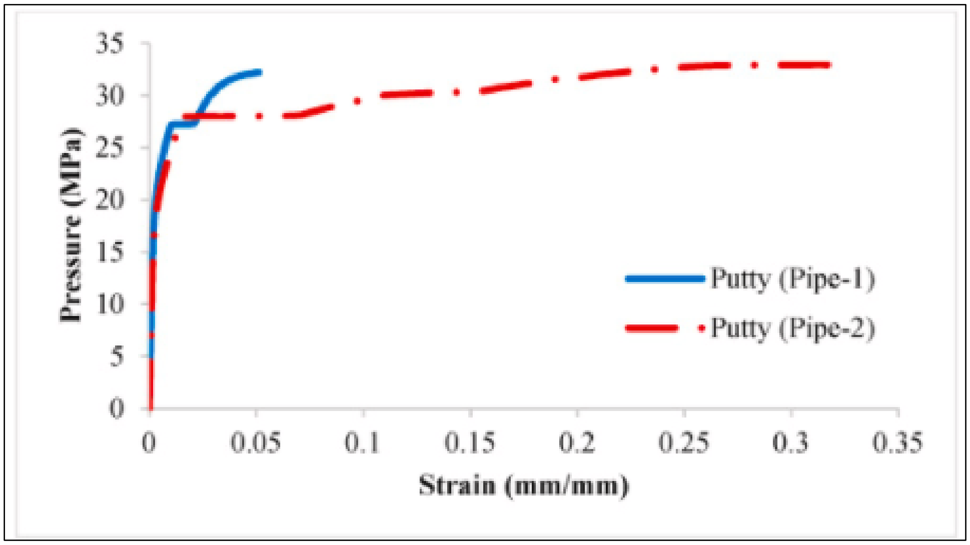

Figure 3 – The pressure-strain curve for the putty in the FE model

Findings showed that the proposed method lead to smaller amounts of pumping wastewater to be discharged, thus leading to less cost and repair time. The repair time for the first case study, with and without the minimum pumping method, can be seen below in Table 4. This would also allow for a reduced pumping rate. A maximum allowable pressure for pipelines was identified to be 41.1 MPa. Repair costs, specifically for wastewater pipelines, and pumping time during repair were able to be reduced by at least 70%.

Table 4 – Pumping costs value for case study 1, Isfahan, wastewater network

Pipe number					**Repair time duration (hour)**	**Method**
35	28	21	14	7		
23.415	23.415	23.415	23.415	23.415	1	*Without minimum pumping method*
46.83	46.83	46.83	46.83	46.83	2	
117.075	117.075	117.075	117.075	117.075	5	
0.223	0.223	0.223	1.226	3.456	1	*With minimum pumping method*
6.913	6.913	4.237	4.237	6.913	2	
26.202	26.202	17.282	17.282	17.282	5	

Summary and Conclusions

Understanding the findings in the articles allow for predictions to be made about structural integrity and pipeline failure, thus allowing for better planning and reduced costs. More importantly, the findings help to narrow down the materials to be used in the prevention of pipeline failure. Further research should first focus on the types of soil or additives to soil that will prevent liquefaction and maintain stiffness throughout the layers. Also, the research should focus on other materials that can reinforce structural integrity to prevent pipeline failure. These materials should allow for load transfer and load sharing, but be better suited for burst pressure. The material should also be lighter in weight as to not greatly affect the weight of the pipe in order to prevent vertical or horizontal displacement. Lastly, the characteristics of the reinforcement materials should not be perturbed by moisture that may come from the soil. The importance of these recent research findings may be introduced to undergraduate and graduate students in an effort to enhance the understanding that is to provide proper safety protocols for the functioning of pipelines without interruptions.

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