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Numerical simulations on shapes and materials and deterioration model of flexible sewer systems

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ABSTRACT

Flexible pipes have been used widely in the sewer pipe system due to its low cost and easy construction compared to rigid pipes. Mechanical strength of various types of flexible pipes, such as PVC and PE, can be increased by their geometric structures. For example, the double-walled tubes were introduced to enhance the radial strength and their material properties were improved by the addition of reinforcing agent such as glass fiber. However, there have been rarely systematic studies regarding detailed material properties for various types of the structure and material. In this study, we numerically analyzed mechanical properties of flexible pipes with various types by the finite element method. As a result, we find the dependence of the deformation behavior both on the type of material and the structure of the pipe for various circumstances. On the other hand, these simulation results could be useful for estimating pipe deterioration process, since many years of observation are needed to estimate the pipe deterioration process but flexible pipes started being used recently and hence there exists rare observed deterioration data. So, we roughly estimate the deterioration process of flexible pipes in terms of geometric structures and materials.

Keywords: Sewer pipe; Polyvinyl Chloride (PVC) pipe; Polyethylene (PE) pipe; Plastic deformation; Deterioration

1. Introduction

Since plastic materials, such as PVC and PE, were discovered, they have been used in many products [1,2]. Especially, they have been used for sewer pipe system instead of concrete [3]. Because of its characteristics such as cheapness, light weight, and easy manipulation, the plastic pipe, that is, the flexible pipe has many advantages over the concrete pipe, that is, the rigid pipe. On the other hand, the diameter of the flexible pipe is rather limited to small values because of its weakness unlike the rigid pipe which is usually used for combined sewer system with large diameter.

For the rehabilitation of the sewer pipe system, it is necessary to assess the deterioration and deformation of the pipes by monitoring and inspection [4]. However, there may not be enough data for the plastic pipe buried underground and moreover the cost for monitoring and inspection are rather expensive.

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Numerical simulation for this will certainly help to overcome these problems. That is, by assessing the deterioration and deformation of the plastic pipe, it is possible to establish more solid plan for the sewer rehabilitation program. While the deterioration of the plastic pipe is due to the chemical reaction with the liquid, the deformation is due to the load by the soil, etc., above. The deformation behavior of the plastic pipe depends not only on the kind of the material but also the structure of the pipe such as multiple walls. We may estimate the deformation of the plastic pipe by the load with the calculation of solid mechanics. This kind of solid mechanics calculation is commonly done by the finite element method (FEM) [5].

In this study, we adopt FEM to estimate the deformation of the plastic pipe in various theoretical circumstances. For the study of the material and structure dependence, we focus on the double-walled PVC pipe and triple-walled PE pipe, which are commonly used in the community. First, we place two rigid slabs above and below the pipe. And we fix the pipe on the slab below and apply vertical displacement of the slab above so that the pipe is deformed between two slabs. This is a typical circumstance to study plastic deformation both theoretically and experimentally. Next, we remove the slab above and apply uniform pressure on the pipe directly and then investigate the deformation of the pipe solely by this pressure. In order to simulate the pressure by the side soil, side pressure is also added. Since the material properties of the plastic will be changed in a long time, the longtime behavior of the deformation of the plastic pipe will be also different from the beginning. With deteriorated material properties for the plastic material, we investigate the deterioration of the plastic pipe.

2. Simulation models: geometry & materials

For the numerical assessment for the mechanical properties of the flexible pipes, FEM was employed. The analysis was performed to address the structural dependency of modulus and stability of the pipes. Mechanical properties can be dependent both on structure and intrinsic material property. It is known that there are two typical shapes of the walls of the plastic pipes: double wall or triple wall (see Fig. 1). Fig. 1(a) and (b) present the cross section of the double-walled PVC pipe and the tripled-walled PE pipe, respectively [6]. The circular pipes are composed of repeated patterns of the unit structures along the pipe axis direction. Gray part in the figure corresponds to void, which is for mass saving of the pipes maintaining its structural stability. Finite element analysis was only performed on the unit structures of the pipes as shown in the figure with proper periodic considerations.

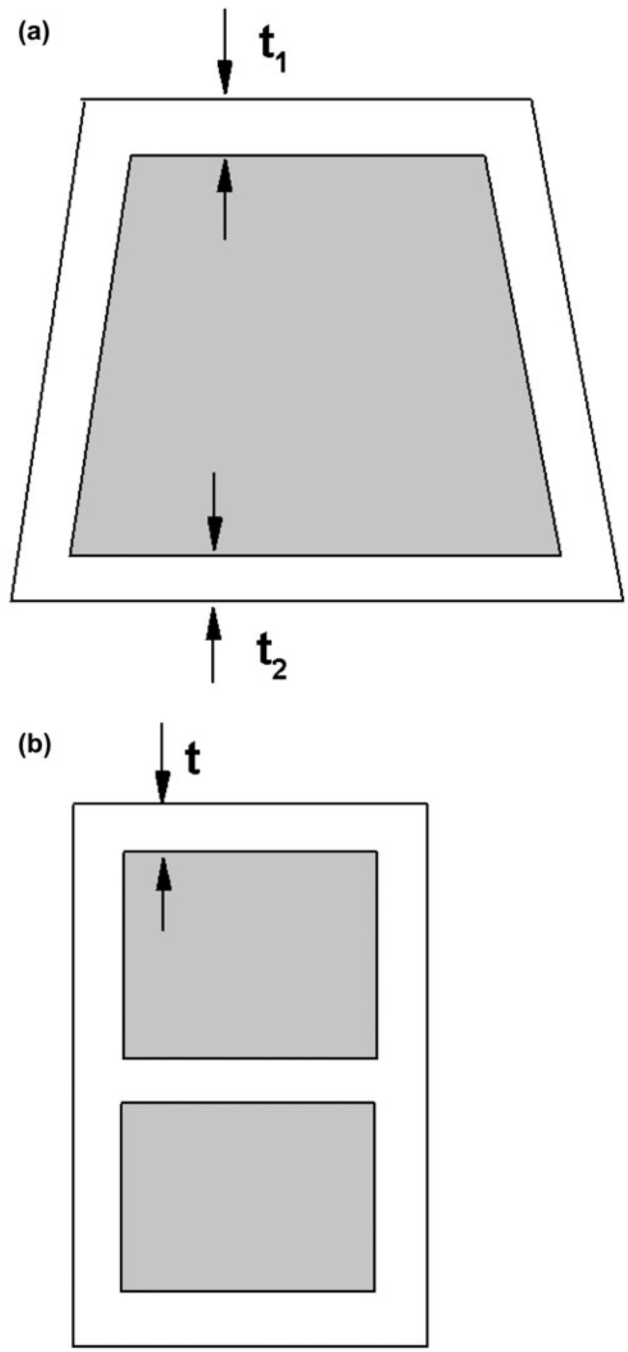

Fig. 1. Cross section of plastic pipe structure: (a) double-walled PVC pipe and (b) triple-walled PE pipe.

In the current simulations, we considered PVC and PE pipes with inner diameter of 600 mm. Results for other diameters may be similar to the results for the case of 600 mm diameter because the aspect ratio of the thickness over the inner diameter would be nearly insensitive to the diameter. The outer diameter of the PVC and PE pipes were 675 and 694 mm, respectively. The wall thickness t_1 was 2.5 mm and the thickness t_2 was 4.5 mm for the PVC pipes, and the wall thickness (t) of the PE pipe was 7 mm.

For the constitutive relations in the analysis, the material properties of PVC and HDPE (HDPE, High-density polyethylene, is used for PE pipe) were introduced in terms of Young's modulus, yield stress and ultimate tensile stress as listed in Table 1 [7–11]. Polymeric materials are known to show wide variations of stress-strain curves depending on the composition and the fabrication process [12]. The PVC and PE, both have high stiffness, but the PE is less strong but tougher than the PVC. The post-yield behaviors are generally very complicated with large variations in real measurement. But, for simplicity in the simulations, we assumed monotonically increasing stress strain curves after the yield points for both materials. The constitutive relations of the PVC and PE are summarized in Table 1 and depicted in Fig. 2.

3. Analysis

3.1. Displacement-controlled analysis

In order to investigate the mechanical properties of a plastic pipe, we apply a displacement load as shown in Fig. 3. Displacement load is a typical type of experiment which can be conducted in a laboratory. The pipe is placed on a concrete slab which has much higher density and stiffness than the plastic. The values of density and Young's modulus for the concrete are 2,400 kg/m^3 and 40 GPa, respectively [13]. Above the plastic pipe, there is a steel slab to give uniform displacement load to the pipe. The values of density and Young's modulus for the steel are 7,850 kg/m^3 and 210 GPa, respectively [14]. It is not needed to include the plastic properties of these slabs for the calculation to see the deformation of the plastic pipe under load. Actually, to get more accurate results focused on the plastic pipe, it is even better to assume much stronger materials for these slabs. Anyway, both steel slab and concrete slab are much stiffer than plastic pipe have very little deformation. Here, we fix the position of the concrete slab (correctly, the position of the bottom of the concrete slab). The friction between plastic pipe and the slabs are set to be enough so that the contacts points between them are fixed.

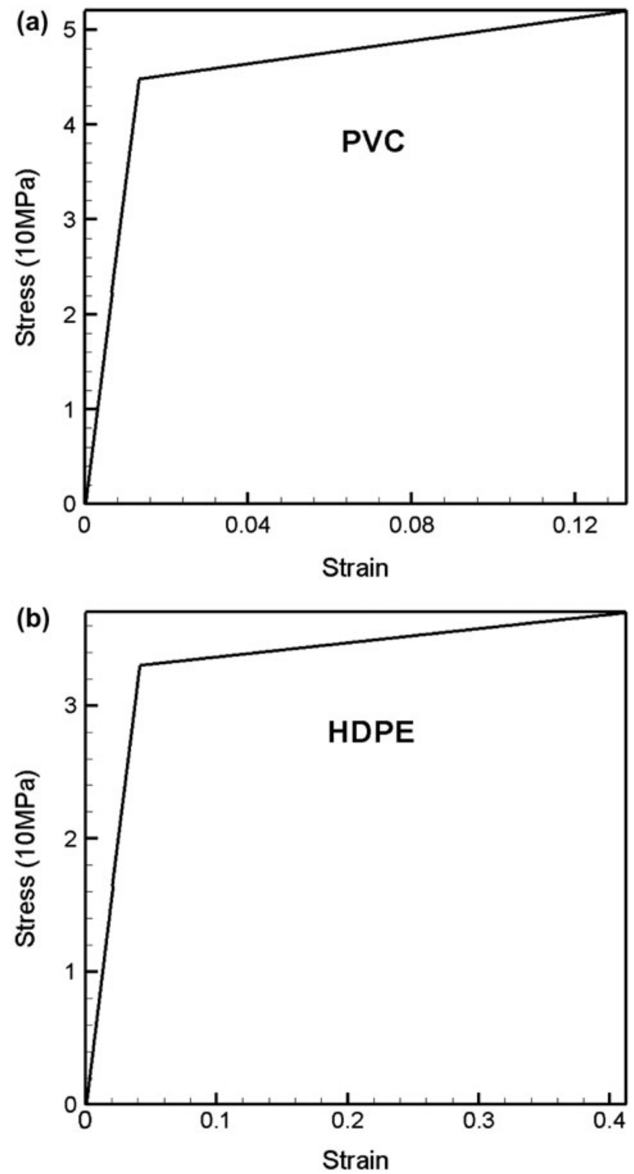

Fig. 2. Stress-strain curves defined for the FEM calculation: (a) PVC and (b) HDPE.

For the FEM calculation, the number of elements must be large enough to obtain good results and

Table 1
Material properties of PVC and HDPE

	Density (kg/m^3)	Young's modulus (GPa)	Poisson ratio	Yield stress (MPa)	Ultimate tensile stress (MPa)
PVC	1,400	3.38	0.38	44.8	52.0
HDPE	950	0.8	0.5	33.0	37.0

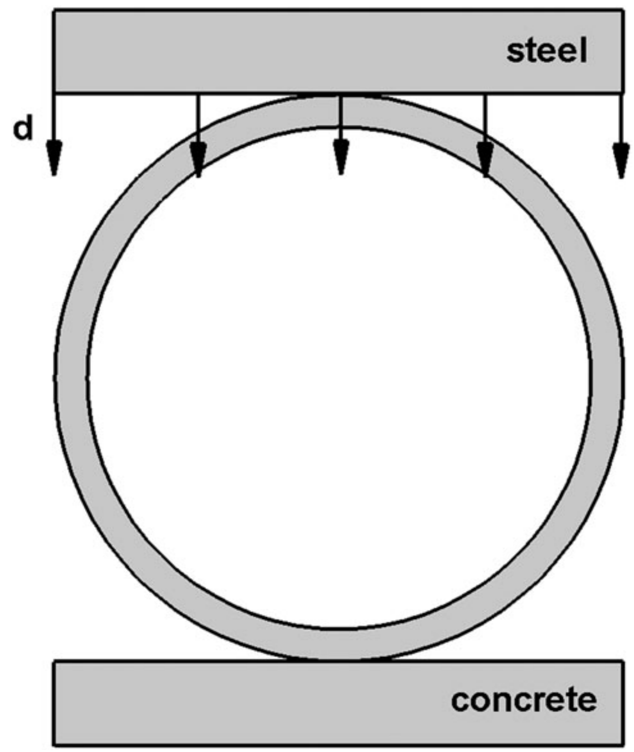

Fig. 3. Displacement load on a plastic pipe.

obviously, as the number increases, that is, as the size of the element becomes small (more fine meshes), the results approach to the correct values. Fig. 4(a) denotes the meshes of the pipe and the slabs before displacement load is applied. Fig. 4(b) denotes the deformed shape of the plastic pipe which is elliptical at cross section and the meshes under finite displacement load applied. When the displacement load is small, the pipe is in bucking mode. That is, as the load is displaced, the shape of the pipe returns to the original. But when the displacement load is large, as the load is displaced, the shape of the pipe does not return to original and stays at the deformed shape. This case corresponds to the plastic deformation.

As the displacement load is increased, the deformation of the pipe is more and the stress will be increased until some point as long as the deformation is in the bucking mode range. Fig. 5 shows this both for PVC and PE pipes. Here, we calculated the total von Mises stress for displacement range 0–0.3 m and plot von Mises stress vs. displacement. Initially, two curves are almost linear and the slope is larger for PVC pipe than PE pipe. This represents that the modulus of PVC is higher than PE. For PVC pipe, linear regime ends around displacement ~0.06 m and beyond this point, the slope is less which is the regime for plastic deformation. The graph almost looks like the stress strain curve for bulk plastic material. On the other hand, for PE pipe, linear regime almost goes up to displacement ~0.25 m. This result represents the yield strain for PE is relatively larger than that for PVC.

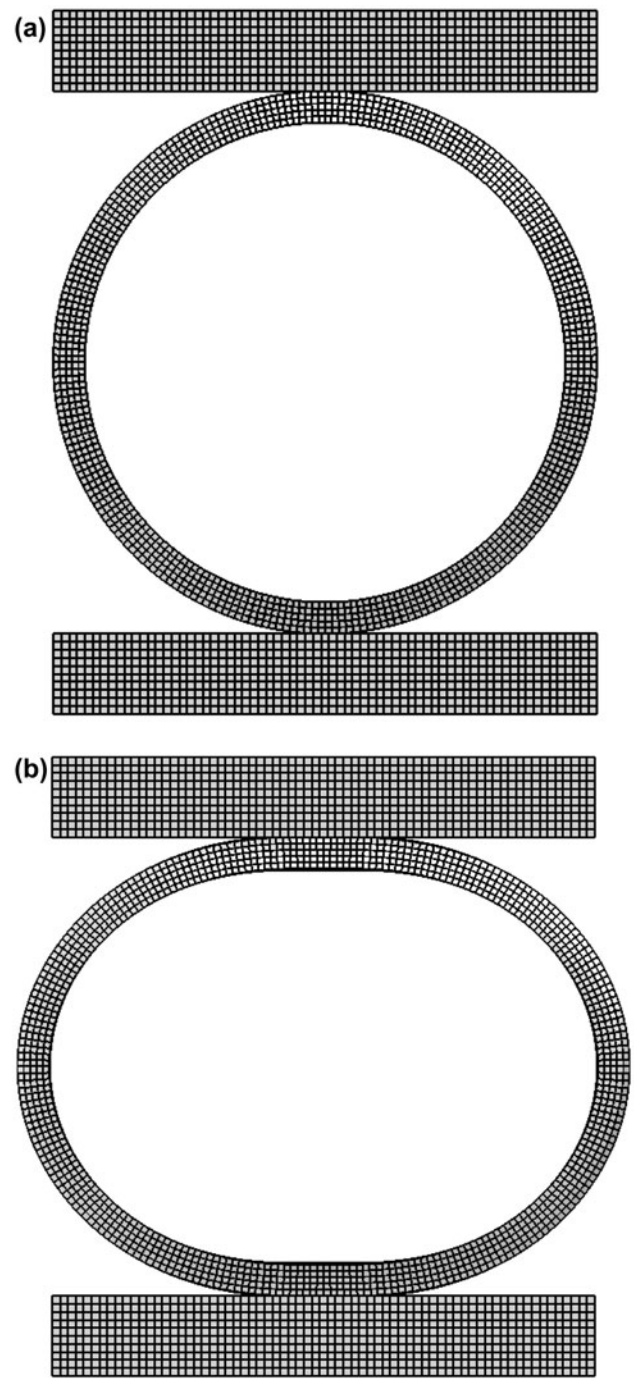

Fig. 4. Elements distribution of pipe and slabs for FEM calculation: (a) before displacement load and (b) after displacement load.

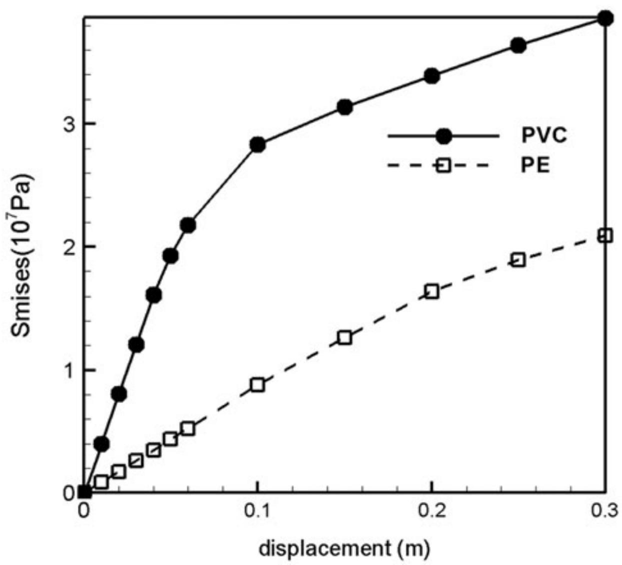

Fig. 5. Von Mises stress vs. displacement for displacement load.

3.2. Pressure-controlled analysis

Unlike the displacement load, where the force on the plastic pipe is through only one contact point between the above slab and the pipe, in reality, the load of the soil above the pipe buried in the ground is through all the hemi-circular part of the plastic. In order to simulate this real case, it is necessary to remove the above slab and apply pressure through all the points of above hemi-circular part of the pipe directly. Fig. 6 shows this case and uniform pressure from above simulates pressure by soil above. The slab below is maintained in the calculation to keep the position of the bottom point of the pipe. The pressure on the surface of the pipe is the normal component of the uniform pressure and therefore, the pressure is the maximum at the center and disappears at the both end in the horizontal direction.

Fig. 7(a) denotes the meshes and the shape of the pipe before pressure is applied. When uniform pressure is applied, the pipe is deformed to elliptical shape as shown in Fig. 7(b). As we increase the magnitude of the uniform pressure, the pipe is deformed more. When the magnitude of the uniform pressure is above some value, the pipe is deformed to the shape shown in Fig. 7(c). The elliptical shape in Fig. 7(b) is the elastic mode where the shape of the pipe returns to its original one with removing the pressure. On the other hand, the shape in Fig. 7(c) is the plastic deformation case where the shape of the pipe does not return to the original one with removing the pressure. The yield points for the plastic deformation depends on the material of the pipe.

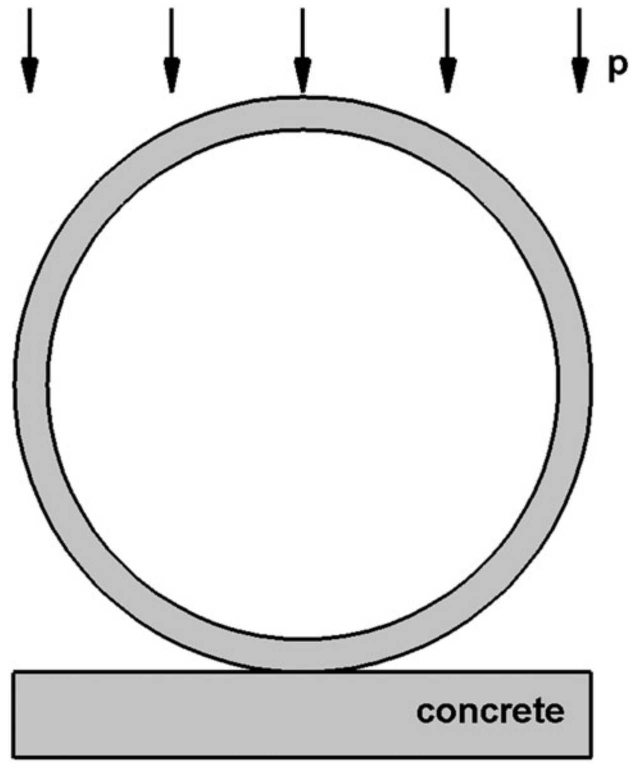

Fig. 6. Uniform pressure acted from above on the plastic pipe.

Fig. 8(a) shows change of the height of the pipe vs. pressure. For both PVC and PE pipe, the graph is linear with constant slope initially and above some pressure, the slope rapidly increases. The yield point for the plastic deformation is about 0.25 MPa for PVC pipe and is about 0.6 MPa for PE pipe. This result again arises from the fact that the yield strain of PE is larger than PVC. The initial slope is slightly larger for PE than PVC, which means PVC material is stiffer than PE material. The capacity of the pipe is proportional to the area of the cross section. Obviously, when the pipe is deformed, the area is decreased. Fig. 8(b) shows the area vs. pressure. Initially, the decreasing ratio is up to a certain point. This is exactly on the yield point in Fig. 8(a). Above this point, the area decreases rapidly and, later, the pipe is deformed as Fig. 7(c), which has very small capacity as a sewer pipe.

3.3. Side pressure

Actually, when a plastic pipe is buried in the ground, the pressure by soil is not only from the above but also from side and from below [15]. As long as the construction is well established, side soil stays and keeps the pipe from deformation, while bottom

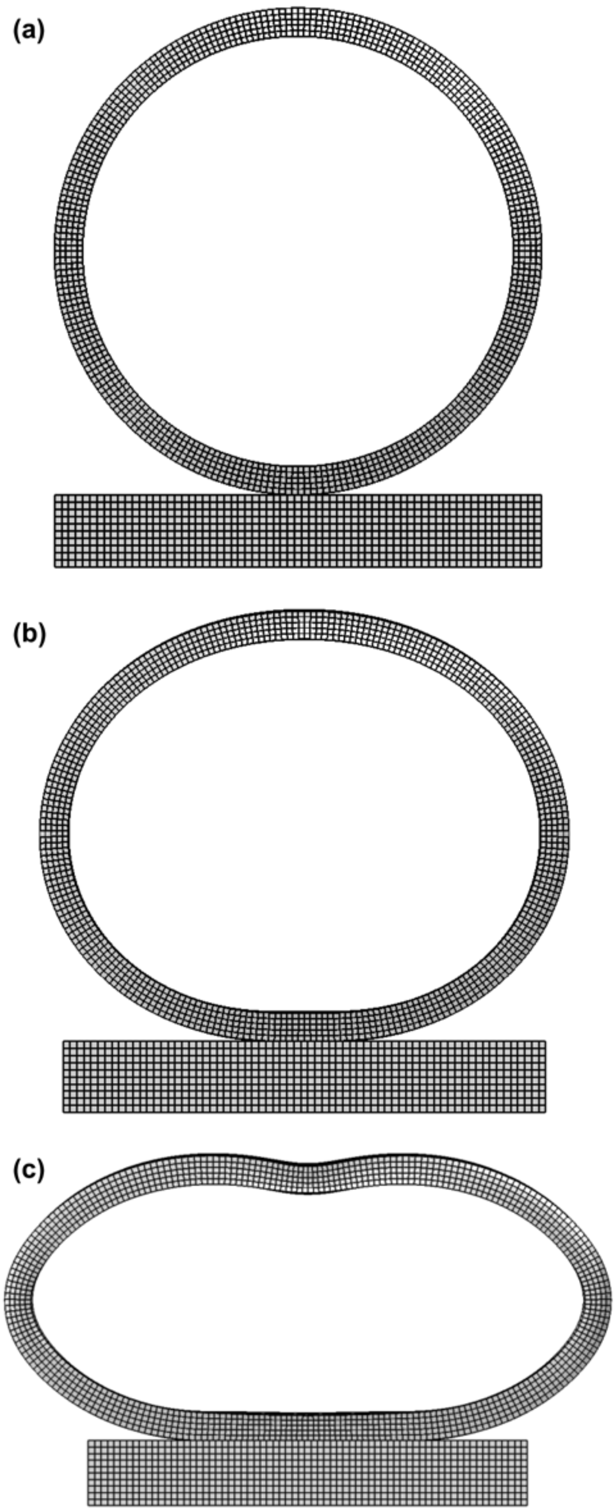

Fig. 7. Elements distribution of pipe and slabs for FEM calculation: (a) before pressure is applied, (b) after small pressure is applied, elastic mode and (c) after large pressure is applied, plastic deformation.

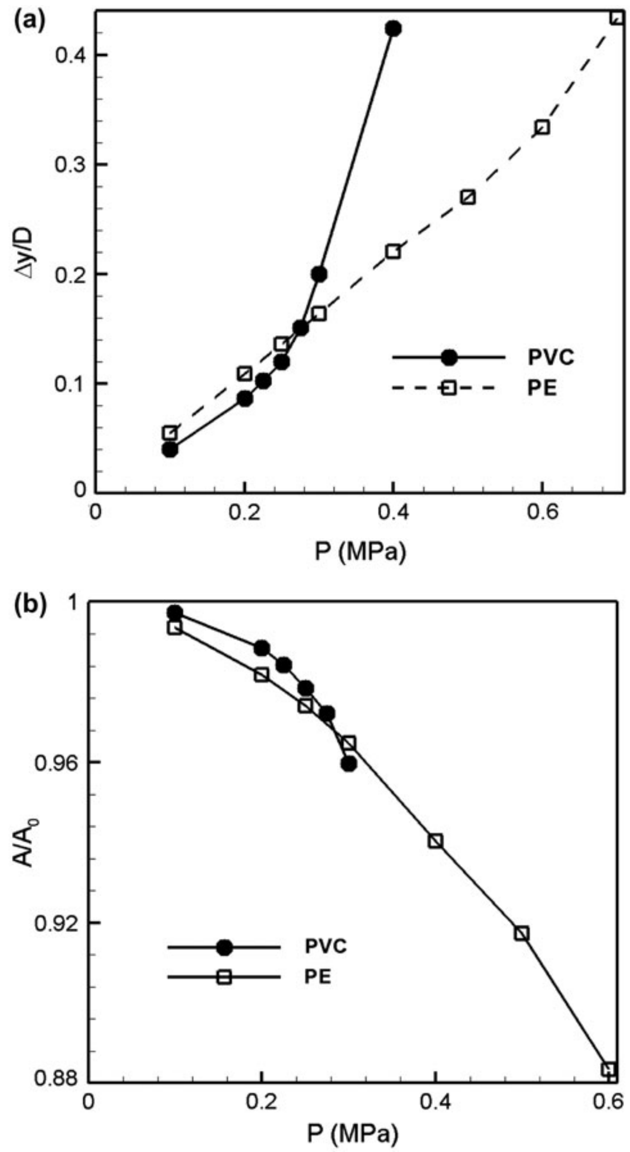

Fig. 8. Uniform pressure applied from above: (a) change of the height of the pipe vs. pressure and (b) cross-sectional area vs. pressure.

soil along with top soil makes the pipe deform. Therefore, Section 3.2 case without side soil has been set to investigate how much the pipe will be deformed when, for example, the side soil is swept into the sewer with inflow and infiltration.

Fig. 9 is the configuration with pressure from all directions for our calculation, where the bottom slab is removed. The magnitude of the pressure below is set to be equal to that of above and the magnitude of the side pressure is set to be 0.7 times of that of above [15]. We may easily conjecture that the results are

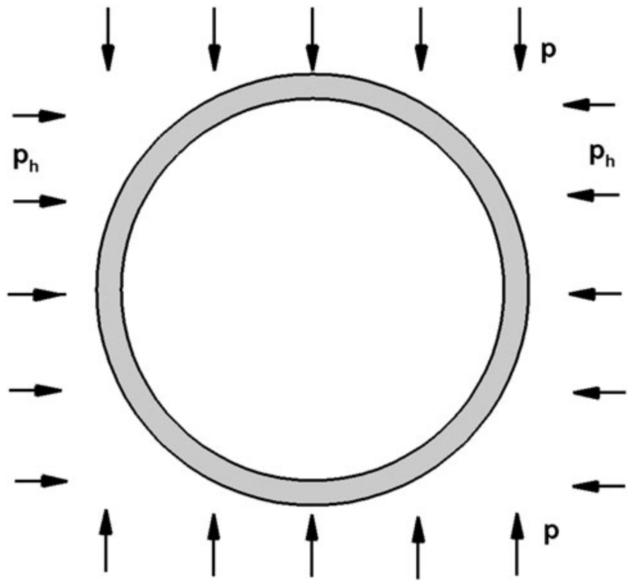

Fig. 9. Uniform pressure acted from above and from side on the plastic pipe.

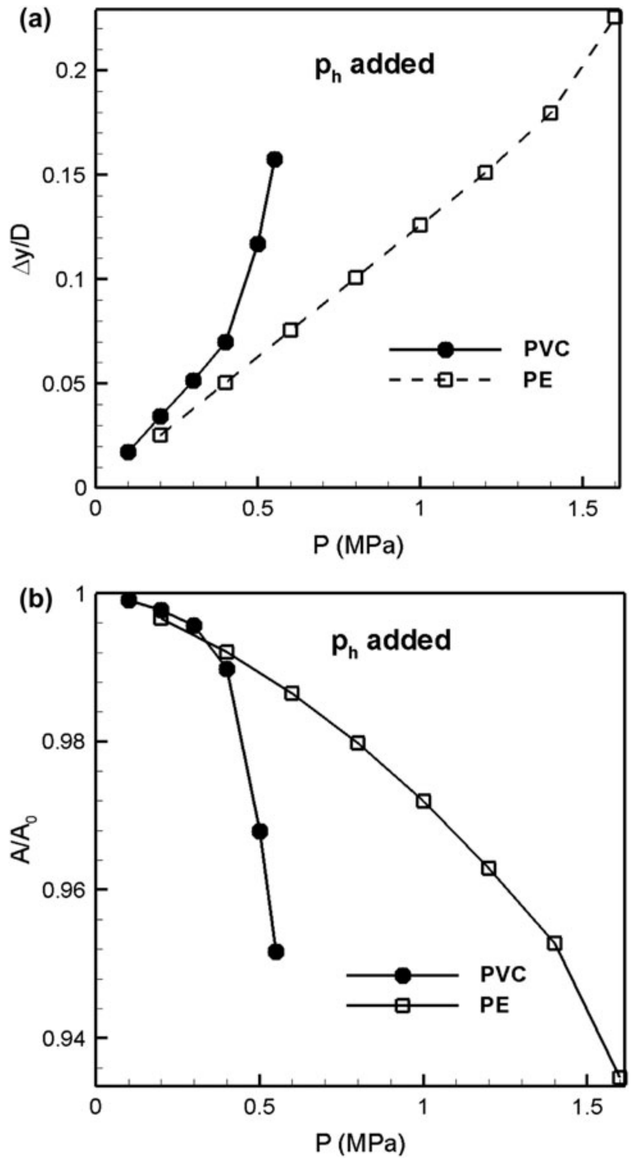

Fig. 10. Uniform pressure applied from above after 50 years: (a) change of the height of the pipe vs. pressure and (b) cross-sectional area vs. pressure.

qualitatively similar to the Section 3.2 and quantitatively different from it. That is, the pressure below plays the same role as the concrete plate and the side pressure keeps the pipe from deformation so that the deformation is less for the same magnitude of the pressure above.

In Fig. 10(a), the change of the height of the pipe is linear in the pressure increase, initially and changes the slope at certain point. This is about 0.4 MPa for PVC pipe and 1.4 MPa for PE pipe. These values are somewhat higher than those of no side pressure in Section 3.2. The slope of PE pipe is about four times the slope without side pressure and the slope of the PVC pipe is about twice the slope without side pressure. Unlike the case without side pressure, the initial slope of PVC pipe is slightly larger than PE pipe. The effect of the side pressure keeping the pipe from deformation is larger for PE pipe than PVC pipe. With the same reason, the cross-sectional area of the pipe for PVC pipe decreases rapidly compared to PE pipe in the plastic deformation regime as shown in Fig. 10(b).

3.4. Deterioration model

The lifetime of the plastic pipe depends on deformation by the load applied and the deterioration of the material properties. The deterioration of the material properties comes from the stress on the pipe and chemical reaction. Usually, the mechanical properties, such as Young's modulus, yield stress, and tensile strength (or ultimate tensile stress), decay with power law. That is, log of such quantities are linear in log of time [2,9,16]. According to long-time behavior of the power-law decay, mechanical properties are rather similar in 10–50 years. We simply focused on the one-time point, 50 years and investigated on the pressure-controlled analysis as in Section 3.2. We set Young's modulus of 50 years to be 30 and 20% of initial values for PVC and PE, respectively, and yield stress and tensile strength of 50 years are assumed 50% of initial values both for PVC and PE [3,17]. We only applied pressure from above as in Section 3.2 and calculated the change of the height and the cross-sectional area of the pipe.

As shown in Fig. 11(a), initial slope of the change of the height is larger for PE pipe than PVC just as Section 3.2. Compared to the initial values at year, the slope is about one-third for PVC pipe and about one-fourth for PE pipe. That is, the difference of two is more at 50 years and this represents the deteriorated modulus. The pressure value for the end of the elastic mode is around 0.1 MPa for PVC pipe, and is over 0.2 MPa for PE pipe. The slope for PE pipe slightly decreased as the pressure increased. This may result from the hardening feature of PE pipe where three walls are collapsed to form thick bulk-like structure for higher pressure, while there is buckling feature of PVC pipe where two thin walls collapsed with empty space in between. The cross-sectional area decreases rapidly for PE pipe compared to PVC pipe as shown in Fig. 11(b) but it keeps linear slope until the pipe comes to the complete plastic deformation regime at pressure 0.2 MPa, where the pipe is deformed as Fig. 7(c).

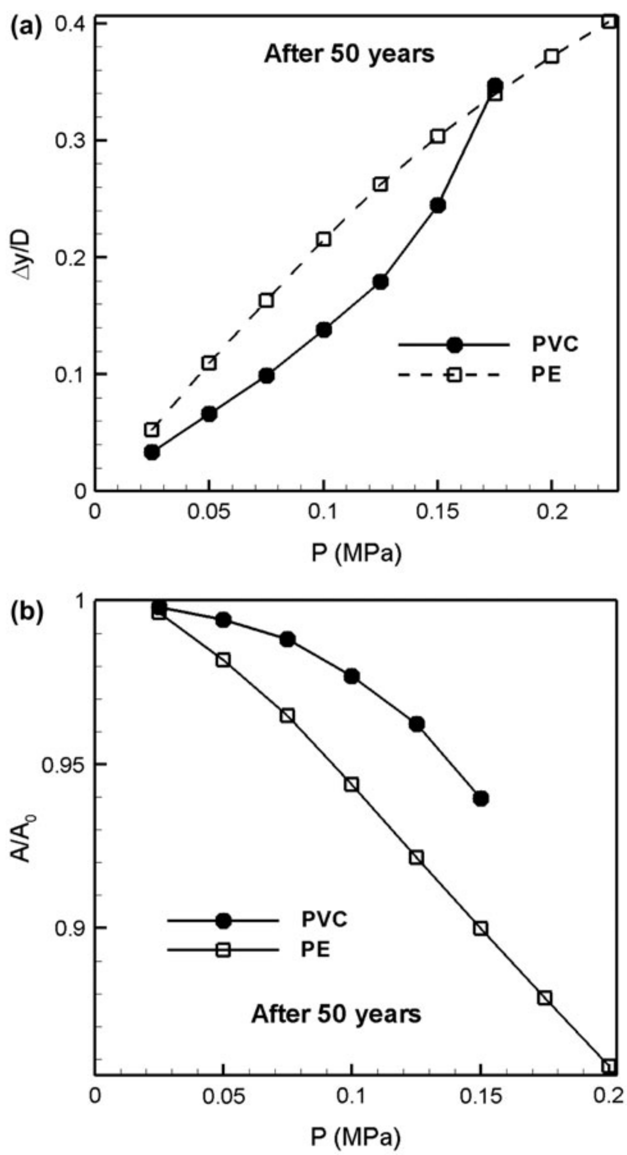

Fig. 11. Uniform pressure applied from above and from side: (a) change of the height of the pipe vs. pressure and (b) cross-sectional area vs. pressure.

4. Conclusions and discussions

In this study, we numerically investigated the deformation behavior of flexible double-walled pipe (PVC) and tripled-walled pipes (PE). Vertical displacement and anisotropic radial pressure were applied to determine stress-strain curves of the pipes. It was shown that the mechanical properties and structural stability were highly dependent on wall shapes as well as the bulk material property. Under the displacement loads, mechanical stiffness of the PVC pipe was much higher than that of the PE pipe, but the yield strain of the PVC pipe was smaller than that of the PVC pipe. In the case of the pressure loadings, little deformations were shown for PVC pipe in small pressure region, but a rapid deformation occurred as the pressure increased. From these results, it is confirmed that the PVC pipe is more rigid, but its energy absorption capability is lower than the PE pipe.

In addition, deterioration analysis was performed in the range of five decades using a simple prediction model. The power law was suggested for the deterioration model, and for the simplicity, the analysis was performed only at one time in five decades. Nonetheless, it was shown that the deterioration model can predict the long-time aging effect on the mechanical properties of the pipes reasonably well.

We think that the different features of two flexible pipes are not only from the different material properties but also from their different geometry such as internal structures, geometry, and thickness of the wall. In the present study, numerical simulation was shown useful for optimal shape design and also for efficient maintenance and rehabilitation of the sewer systems. For example, it can be applied to predict the performance of the sewer system when completely new design and materials are being considered to be developed. However, experimental investigations are definitely to be incorporated with the numerical simulations for more realistic predictions.

Acknowledgements

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