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DAMAGE MECHANISM OF PVC DRAINAGE PIPE CONNECTED TO HOUSE WITH HIGH SEISMIC PERFORMANCE

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Abstract

Recently, detached houses with higher seismic grade have become popular in Japan. Because of their high rigidity, the houses tend to show minor structural deformation and slip on the ground during strong motions. In fact, some inspections in suffered areas in the 2016 Kumamoto Earthquake indicate evidence of house slippage. This slippage may dissipate input energy to the houses, and mitigate structural damage. However, it gives considerable relative displacement to pipelines which are connected to the house base and embedded in its surrounding soil. For base isolated houses, flexible pipes are usually used because relative displacement is considered in their design. On the contrary, relative displacement from house slippage is usually unexpected in design and standard PVC pipes are generally used for non-isolated houses. Because of this, the pipes may be significantly damaged due to the house slippage. Damages of the pipelines probably induce fatal malfunction of the houses, and their residents are not able to stay in the houses until restoration of their function. Therefore, it is important to avoid the pipeline damages in order to achieve highly resilient society. However, damage examples of PVC drainage pipes are significantly insufficient, and there is no assessment method on their responses during strong motions.

In light of this, a series of E-Defense shake table test has been performed by using a full-scale test specimen. The specimen was composed of a soil container, well-compacted sandy soil ground in the container, a wooden house on the ground, and five PVC drainage pipes. One of the pipes had a flexible portion and expansion joints, and the others had a non-flexible crank-shaped portion. All of them were fixed to the house base at one end and connected to a catch basin at the other end. Strain gages were placed around elbow portions of the PVC pipes. Inputting a three-directional motion recorded in 1995 Hyogo-ken Nanbu Earthquake, the house slipped approximately 0.25 m and all the pipes except for the flexible one were fatally collapsed. After the E-Defense shake table test, a static load test of the PVC drainage pipe with no soil around was also conducted in order to obtain more fundamental data. As a result of these tests, the follows are drawn; 1) relative displacement induced by house slippage fatally damaged drainage pipes with no flexible portion, 2) appropriate installation of flexible portions can protect functions of drainage from large ground motions, and 3) mechanism of strain development along pipes are highly dependent on fixity at house foundation, relative depth of pipe embedment to one of foundation, and their surrounding soil as well as amount and direction of foundation slippage.

In this paper, brief descriptions of the tests and some of their representative results are provided. The test results are compared each other. Based on the discussion, mechanism of strain development and failure along the drainage pipes is described.

Keywords: Shaking table test; wood house; functionality; PVC drainage pipe

1. Introduction

Because seismic activity is quite high in Japan, a large number of structures have suffered from significant damages in the past earthquake disasters. Because of this experience, detached wood houses with high seismic performance are recently getting popular. For instance, houses with seismic grade of three have 1.5 times larger performance than one defined in design standard. To make higher performance, additional bearing walls are usually placed, and therefore, the houses become more rigid. Because of their higher rigidity, the houses tend to have less structural damage, but slip on the ground during strong motions. In fact, some inspection results after the 2016 Kumamoto Earthquake implies evidence of house slippage as shown in Fig. 1. Gravel was placed on the ground around the house, but soil originally beneath the house appeared due to the house slippage. In this figure, a pipe for rainwater drainage was disconnected. It probably resulted from relative displacement between the house and the ground induced by the slippage.

Fig. 1 – Evidence of house slippage (coutesy of Ichijo Co.,Ltd.)

Various lines for essential utilities are connected to detached houses; for instance, electricity, water and gas supply, and rainwater and sewage drainage. Disorder of one or more of them may fatally lose function of the houses, and their residents can not be stay in the house until restoration of their function. Therefore, in some cases, it is critical to avoid damage of essential utilities in order to reinforce city resiliency. In general, electricity is supplied through flexible cables. Water and gas are distributed by head and pressure, and therefore, flexible pipes or tubes can be used where large displacement is expected. However, drainage pipelines usually work by natural grade, so, drain system is considerably sensitive to deformation of the pipes.

In light of the above, a series of E-Defense shake table test has been performed by using a full-scale three-story wood house. The house specimen was built on the soil, and PVC drainage pipes as one of the most critical elements, are placed in the soil and connected to the house. In addition, a static loading test of PVC pipes was conducted after the shaking table test. In this paper, details of the PVC drainage pipes including test setup and instrumentation for both of the tests are described. Based on data recorded, deformation and failure mechanism of the PVC pipes are discussed.

2. E-Defense Shaking Table Test

In this paper, information related to PVC drainage pipes is described. More details of this shaking table test including specification of a wood house are available elsewhere [1][2].

2.1 Descriptions of shaking table test

Test setup of PVC drainage pipes is illustrated in Fig. 2. The test specimen was composed of a RC soil container, soil, pipelines including PVC drainage pipes, and a wood house. Five of PVC drainage pipes, defined as Sections A to E herein, were embedded in the surrounding soil and connected to the house foundation. Because the main pipe was inclined at 2/100, each section had different depth of embedment. One of the sections, Section A, was seismically reinforced by using a flexible pipe and expansion joints as shown in Fig. 3. The flexible pipe used was bellows tube and interconnected between a catch basin and a pipe from inside of the house through one of the expansion joints with allowable displacement of ±60 mm. Rotation at the expansion joint had no restriction. Another flexible pipe was installed in a sheath pipe embedded in the house foundation. Details of the other sections are illustrated in Fig. 4. Sections B to E had a crank-shaped portion with no flexible pipe in the surrounding soil. In Sections B and C, the flexible pipe was placed in the sheath pipe. The sheath pipe was laid across the bottom of the foundation in Section B, but fully embedded in the foundation in Section C. Sections D and E had no sheath pipe. In these sections, the pipes from inside of the house were led to outside of the house through void tubes embedded in the foundation, and the upper elbows were above the ground surface. The PVC pipes used in this test were VU pipes typically applied for drainage in Sections A to D, and VP pipes in Section E. Because the pipes were 75A and 100A in diameter inside and outside of the house, respectively, reducing elbows were used as upper elbows as shown in Figs 3 and 4.

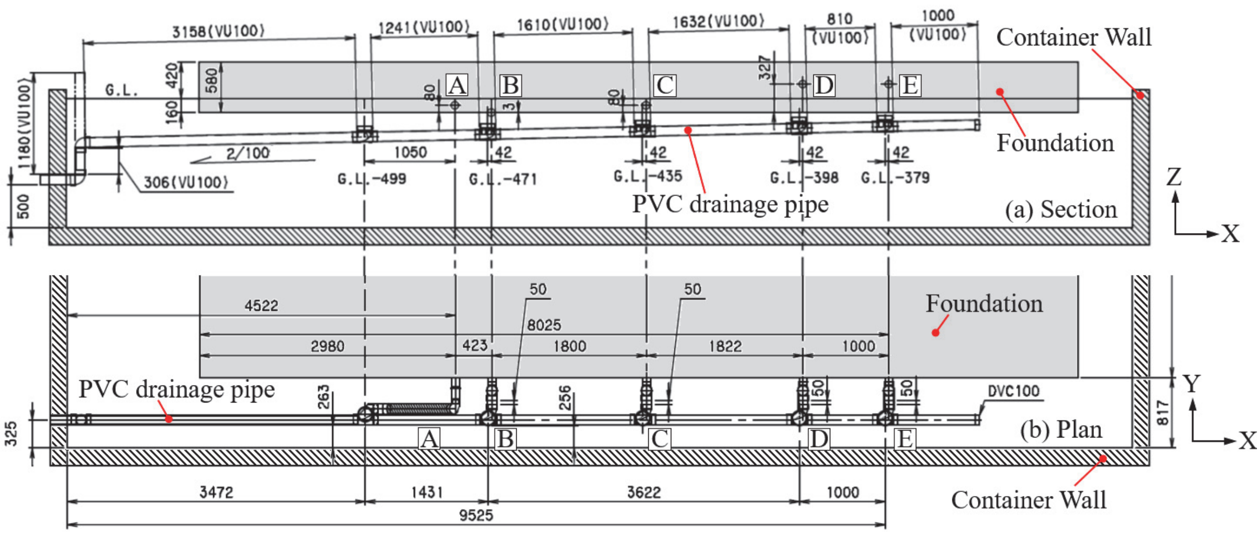

Fig. 2 – Test setup (shaking table test)

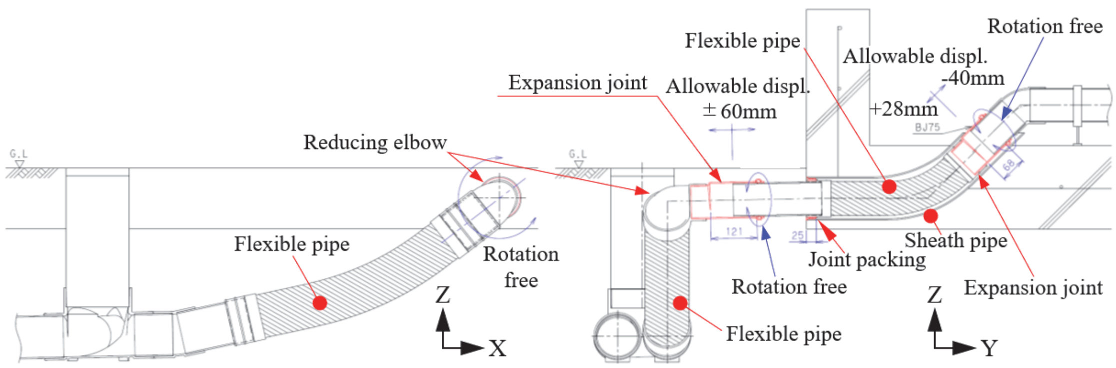

Fig. 3 – Details of Section A

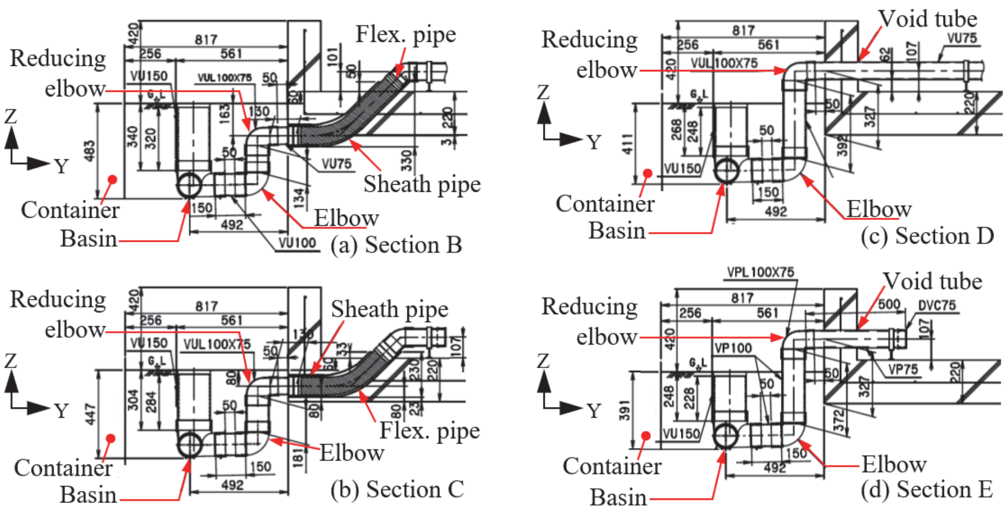

Fig. 4 – Details of Sections B to E

Placement situation of the PVC pipes are shown in Fig. 5. First of all, the soil material, No. 6 Ube silica sand, was poured into the container and compacted by tamping rammers with spreading lift of 10 cm. Relative density of the sand was approximately 78 %. Results from Swedish sounding tests indicated its average bearing capacity was 85 kN/m^2. After that, the house foundation was built on the soil, and the pipes were placed at designed location by excavating the surrounding soil. More details of this sand layer are available elsewhere [3], Figs. 5a and 5b show an overview and one of the expansion joints in Section A, and Figs. 5c to 5f show Sections B to E. Finally, the soil was poured and compacted up to designed ground level (Fig. 5g).

Strain gages were used to capture dynamic behaviors of the PVC drainage pipes. Assuming seam of the elbows were one of the most critical portions, the gages were placed along the seam. A top half of the reducing pipes and a bottom half of the lower elbows were instrumented as shown in Fig. 6.

Input motions applied to the specimen is summarized in Table 1. Small level random motions with wide range frequency components were also input to the specimen between the motions in this table to see change of dynamic characteristics of the specimen. The data obtained in these motions are not mentioned herein because insignificant slippage of the house observed in these motions developed ignorable strain along the pipes.

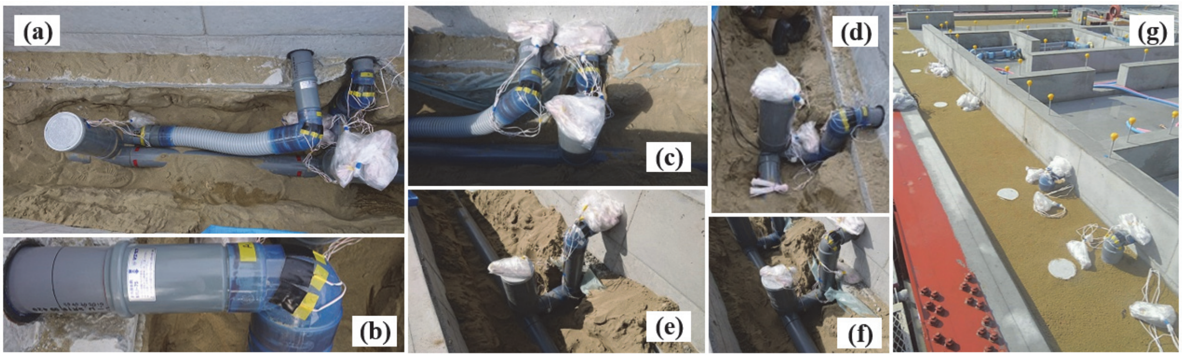

Fig. 5 – Placement of PVC drainage pipes

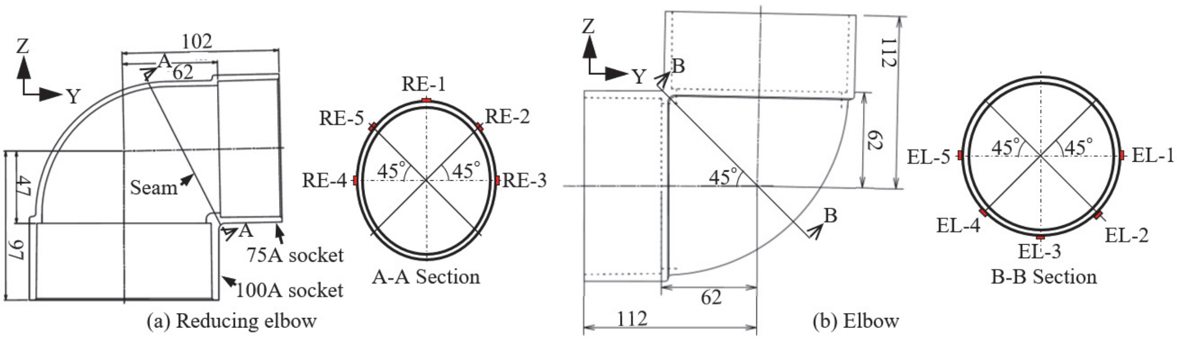

Fig. 6 – Locations of strain gages around elbow portions

Table 1 – Summary of input motions

No.	Motion	Amplitude	No.	Motion	Amplitude
1	JMA Kobe	25 %	4	JR Takatori	50 %
2	JMA Kobe	50 %	5	JMA Kobe	100 %
3	JR Takatori	25 %	6	JR Takatori	100%

2.2 Slippage of house foundation

Time histories of foundation slippage are plotted in Fig. 7. The slippage herein is an average displacement measured by laser displacement transducers at the four corners of the house in both of the X- and Y-directions. At input of JMA Kobe 100 % and JR Takatori 100%, some of the transducers could not record the displacement in the large input motions. Also, the displacement time histories showed considerable rotation around Z-axis and rocking behavior of the house, but it is assumed that these behaviors gave minor influence to the behaviors of the pipes herein for qualitative discussion. It is noted that the motion of JR Takatori 100 % was input in horizontally reversed directions to avoid excessive accumulation of the house slippage in both of the X- and Y-directions. This figure indicates that residual slippage was less than 1 mm after the first 4 input motions, and the house significantly slipped in JMA Kobe 100% and JR Takatori 100 %.

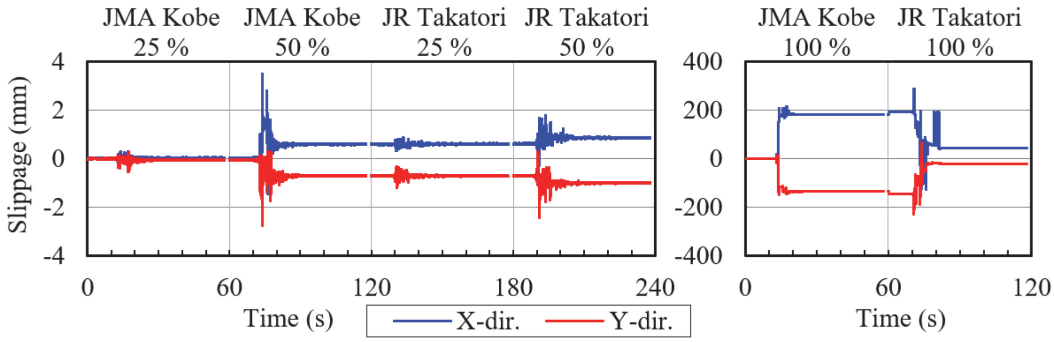

Fig. 7 – Time histories of house slippage

2.3 Damage inspection during and after shaking table test

Damage inspection of PVC pipes was performed during shaking through video cameras. It was observed that the reducing elbow in Section D was fatally ruptured in JMA Kobe 100%. Damage conditions of Sections A to C could not be captured from the videos because these pipes were fully embedded in the surrounding soil. Section E with VP pipes had minor damage in the 100A socket of the reducing elbow, but the reducing elbow itself showed no rapture.

After all the shaking, another damage inspection was performed by excavating soil around the PVC drainage pipes. Fig. 8a shows Section A with insignificant damage. As shown in Fig. 8b, the expansion joint was contracted approximately 45 mm and a rubber packing was pulled out from the foundation. The rubber packing can be easily returned to original position by hand, and Section A was still functional even though the house slippage was quite large. The house slippage was about 140 mm in the negative Y-direction and approximately 110 mm in the positive Y-direction in JMA Kobe and JR Takatori 100 %, respectively, and therefore, the residual slippage of the house was approximately 30 mm (Fig. 7). So, 45 mm contraction of the expansion joint implies this 15 mm difference induced pull-out of the packing. Because 140 mm slippage was beyond the capacity of the expansion, ±60 mm, it was absorbed by the embedded flexible pipe as well as the expansion joint. In JMA Kobe 100 % motion, the soil around the flexible pipe was pushed in the negative Y-direction by the house slippage, the flexible pipe could be deformed with the surrounding soil easily. However, the soil around the flexible pipe stayed in JR Takatori motion because the house slipped in the positive Y-direction, and therefore, flexibility of the flexible pipe may be reduced by reaction from the surrounding soil. It may result in 15 mm difference between the residual slippage of the house and the contraction of the expansion. So, the combination of the expansion joint and the flexible pipe worked quite well in this test, but more modification is probably necessary against house slippage in pulling direction.

Figs. 8c to 8f show damage condition of Sections B to E, respectively. The lower elbows as well as the reducing elbows were fatally raptured in Sections B to D. The reducing elbow in Section E had only minor damage as mentioned above, but the bottom portion of the vertical pipe was totally failed. Based on the inspection, it is obvious that Sections B to E completely lost their function. It is noticeable that the fatal rupture in Sections B to E was not happen at instrumented area.

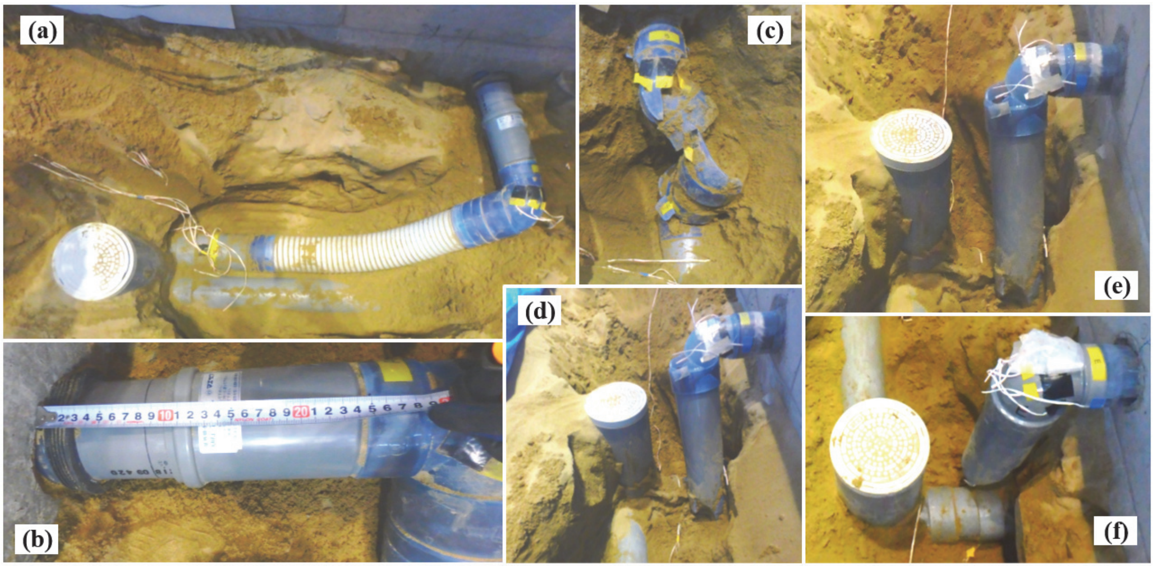

Fig. 8 – Damage inspection of specimens

2.4 Dynamic behaviors of PVC drainage pipes

Based on records obtained in the shaking table test, deformation development and failure mechanisms are discussed herein. Figs. 9a, 9b and 9c show time histories of axial strain around the reducing elbows in the first four input in Sections A, C and E, and Figs. 9d and 9e show ones around the lower elbows in Sections C and E. Strain time histories in Sections B and D showed similar tendency to ones in Sections C and E, respectively. According to these figures, the follows are drawn: 1) Axial strain in Section A was smaller than ones in the other sections. It implies that the flexible pipe and expansion joint could reduce strain around the reducing elbow, 2) Even though the house slippage was less than 1 mm, approximately 750 micro axial strain was remained in the reducing elbows in Sections C and E. In addition, insignificant axial strain appeared in the lower elbow in Section C, but about 400 micro axial strain was remained in the elbow in Section E. It implies strain along PVC drainage pipes is accumulated even in small level earthquake motions.

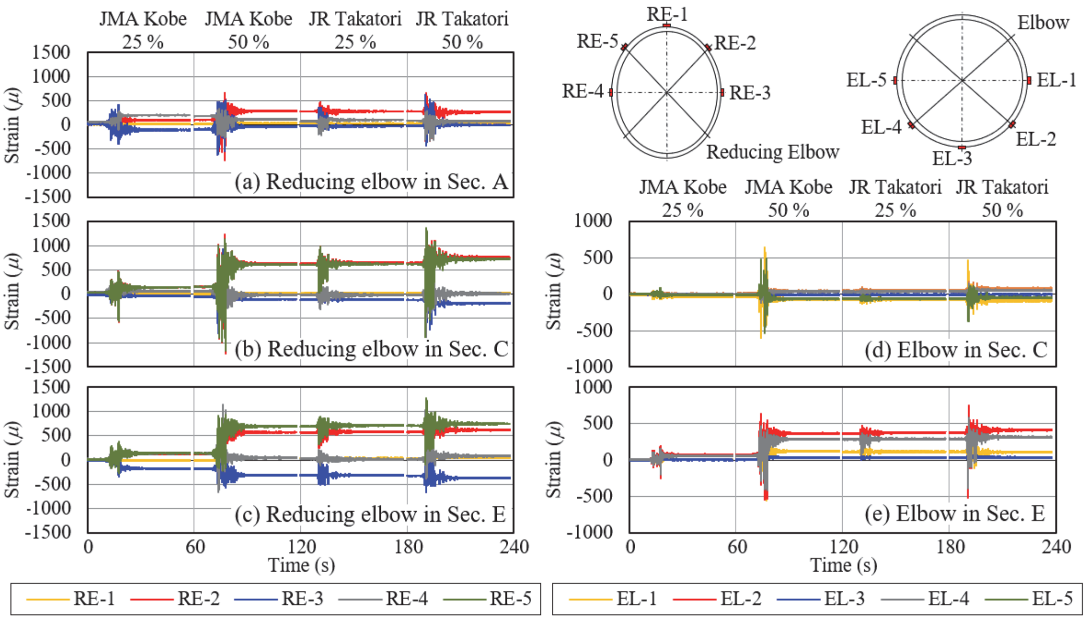

Fig. 9 – Time histories of axial strain around elbows at input of JMA Kobe 25 % to JR Takatori 50 %

Distributions of residual axial strain around the reducing elbows and the lower elbows after input of JR Takatori 50 % are plotted in Fig. 10. In this figure, the top half is distribution in the reducing elbows, and the bottom half is one in the lower elbows. It is noted that slightly larger displacement was applied to Sections D and E than to Sections A to C because of rotational component of the house slippage. The distributions indicate the follows: 1) Axial strain in Section A was considerably smaller than in the other sections. 2) In all the sections, insignificant strain appeared at the top of the reducing elbows, RE-1. On the other hand, RE-2 and RE-5 showed considerable tensile strain. 3) In all the sections with the lower elbows, EL-3 gages recorded insignificant strain. 4) Most of axial strain concentratedly appeared in the reducing elbows in Sections B and C. However, considerable axial strain was observed at EL-2 and EL-3 in the lower elbows as well as in the reducing elbows in Sections D and E. It may result from different confining pressure from the surrounding soil; that is, Sections D and E with smaller depth of embedment had smaller confinement from the soil, the lower elbows in these sections could deform more flexibly than Sections B and C. It implies the soil characteristics considerably influence to the pipe deformation and failure.

Fig. 11 shows relationships between axial strains at RE-2 (Figs. 11a and 11b) and RE-3 (Figs. 11c and 11d) in Section C and the house slippage in X- and Y-directions in the first four input motions. Based on this figure, the follows are drawn: 1) Axial strain at RE-2 tends to be propotional to the house slippage in Y-direction. It is noticiable that tensile and compressive strain appeared in the negative and possitive Y-directional slippage, respectively. 2) Axial strain at RE-3 is propotional to the slippage in X-direction. Becauase strain at RE-4 shows almost out-of-phase time histories with RE-3, it indicates that strain at RE-3 was induced by bending due to the house slippage in X-direction.

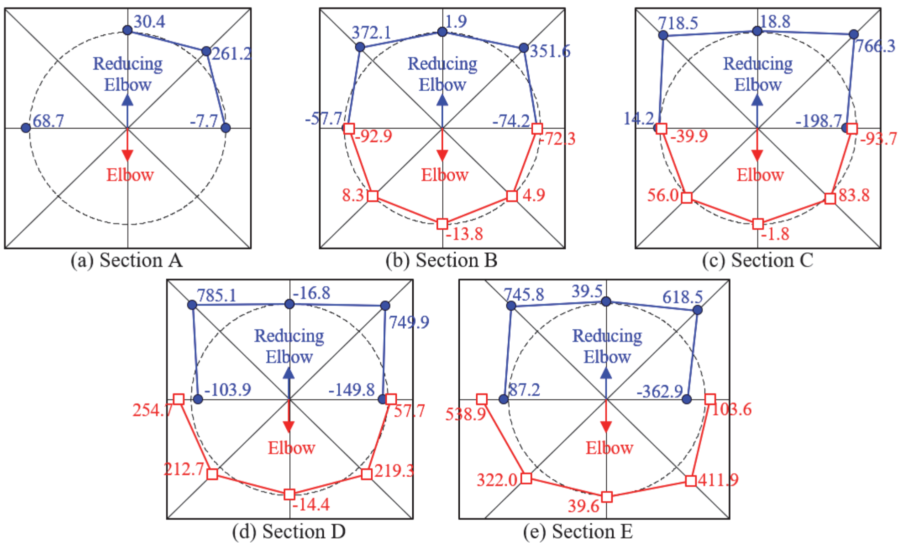

Fig. 10 – Distribution of residual axial strain around elbow portions after input of JR Takatori 50 %

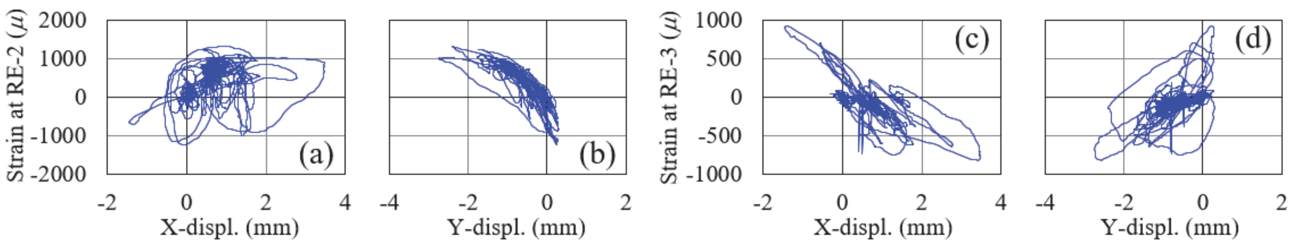

Fig. 11 – Relationship between axial strain and house slippage in Section C in the first 4 input

Time histories of axial strain around the reducing elbows in Sections A, C and E in JMA Kobe 100% are shown in Figs. 12a, 12b and 12c, and ones around the lower elbows in Sections C and E are plotted in Figs. 12d and 12e. It is noted that the strain in this figure is not strain at failure because the gages were not placed at the ruptured portions. So, it is assumed herein that the PVC pipe was collapsed near the gage when discontinuity of strain time histories appeared at that gage. Based on Fig. 12a, the maximum strain reached at approximately 6000 micro strain, but there was no jump observed in Section A. On the other hands, significant jumps of strain records were recorded at 13.85 s in Sections C as shown in Fig. 12b. These jumps may correspond to the fatal rupture of the reducing elbows in Section C as observed in Fig. 8d. Again, considerable strain jumps appeared in some of the gages in Fig. 12c, but they are less significant than in Fig. 12b. These relatively small jumps may imply minor damage of the pipe, such as the 100A socket failure. Also, significant discontinuity of strain appeared in the lower elbow in Section C at 13.87 s, slightly after the strain jumps in the reducing elbow as shown in Fig. 12d. It may correspond to the fatal damage of the lower elbow in Section C. Relatively minor strain jumps were observed in Fig. 12e at 13.85 s in Section E. It may be when the vertical pipe was fatally collapsed and accumulated strain in the lower elbow was released.

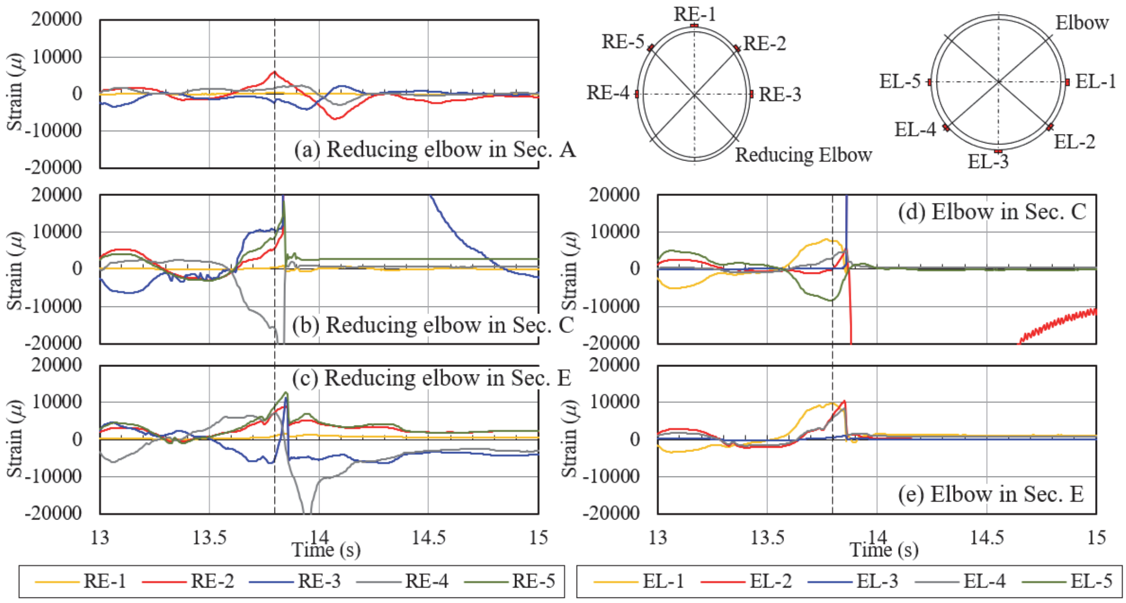

Fig. 12 – Time histories of axial strain around elbows at input of JMA Kobe 100 %

Fig. 13 shows distribution of axial strain around the reducing and lower elbows at 13.8 s in JMA Kobe 100%, right before the significant strain jumps. This figure shows different tendency from Fig. 10; that is, significant strains appeared on the sides of the reducing and lower elbows. RE-3 and RE-4 in the reducing elbow, and EL-1 and EL-5 in the lower elbow show different sign of axial strain. It indicates that the elbows were significantly bent. In Sections B and C, the reducing and the lower elbows were bent in the same direction, however, these elbows deformed in the opposite direction in Sections D and E.

Relationships between axial strain at RE-2, RE-3, EL-1 and EL2 and the house slippage in X- and Y-directions are shown in Fig. 14. All the strains tend to be highly dependent on the house slippagein X-direction. It implies deformation at gage locations was correlated to bending around the vertical axis, but it is noted that the fatal failure of the elbows was not happen in the instrumented portions as mentioned above.

Based on the above results from the inspection and data analysis, a possible failure mechanism of the drainage pipes is illustrated in Fig. 15. At the fist stage, rotational deformation around the reducing elbows was partially restricted because of rotationally fixed boundary connection at the surface of the house foundation, and therefore, tensile rupture was generated around the 100A socket in the reducing elbow as shown in Fig. 15a. If the PVC drainage pipes were in the air without the surrounding soil, all the strain along the pipes were released and no more failure appeared. However, large displacement of the surrounding soil was induced due to embedded portion of the house foundation, and pushed the pipes. In Sections B and C, because the depth of the embedment of the pipes was large relative to one of the house foundation, the lower elbows may be fatally failed around the socket to the vertical pipes by bending deformation (Fig. 15b). On the other hand, in a case if the depth of embeddment of the pipe was relatively small comparing with one of the foundation like Section E, the bottom portion of the vertical pipe may be failed by shear deformation as shown in Fig. 15c. In addition, deformation development mechanism due to the house slippage in X-direction is shown in Fig. 16. Sections A, B and C bent in the opposite direction to Sections D and E as mentioned above. It probably resulted from different fixity in rotation around the vertical axis; that is, the void tubes in Sections D and E provided less rotational restriction than in the other sections. Based on the

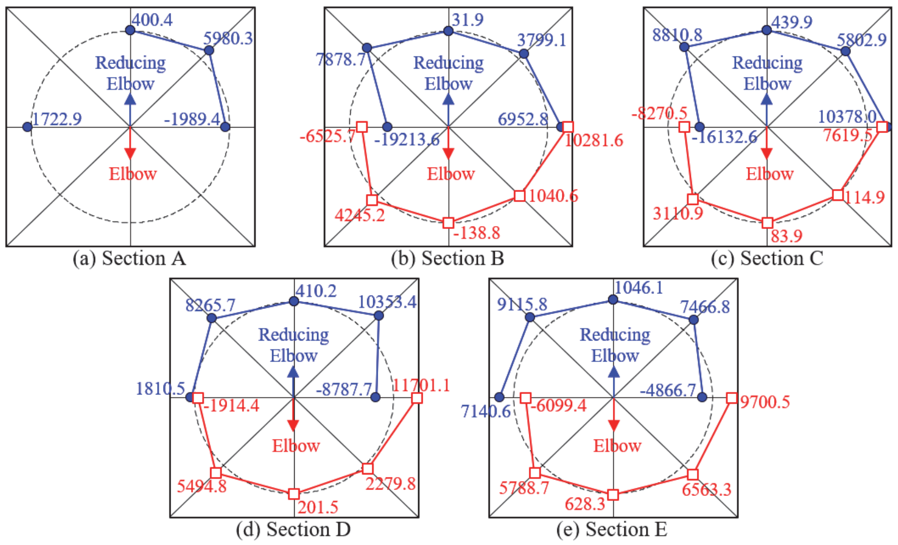

Fig. 13 – Distribution of axial strain around elbow portions at 13.8 s in JMA Kobe 100 %

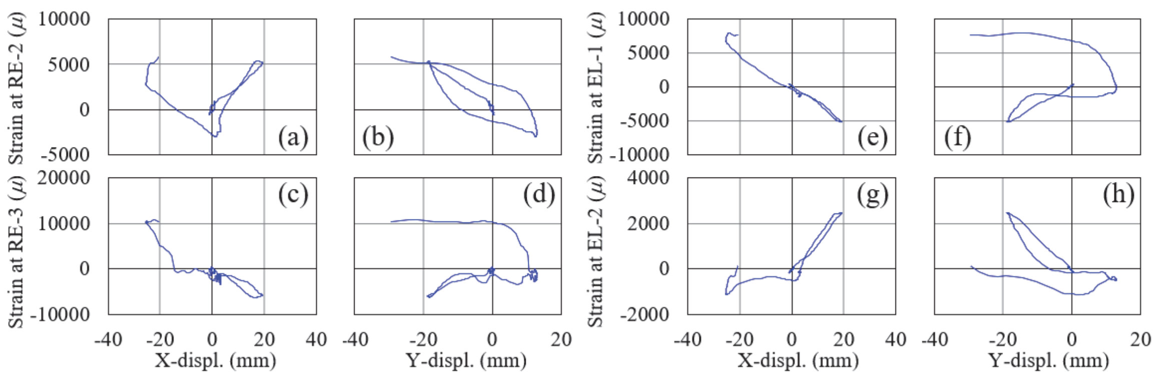

Fig. 14 – Relationship between axial strain and house slippage in Section C in JMA Kobe 100 % up to 13.8 s

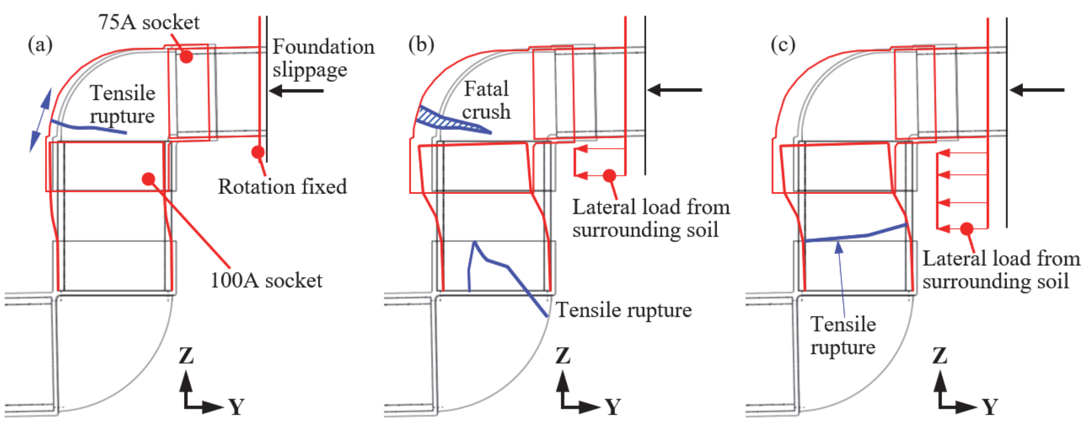

Fig. 15 – Possible failure mechanism due to house slippage in Y-axis

discussion herein, it can be reasonably hypothesized that deformation and failure mechanism of the PVC drainage pipes are highly dependent on fixity at the surface of the house foundation, relative depth of embedment of the pipes to the house foundation, and the surrounding soil as well as the amount and direction of the house slippage.

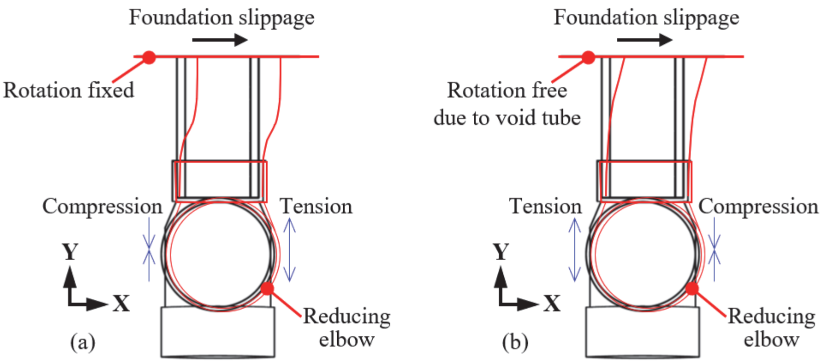

Fig. 16 – Deformation development due to house slippage in X-axis

3. Static Loading Test

3.1 Descriptions of static loading test

For the above shaking table test, there was no time to place strain gage along the straight portions of the pipes because drainage pipes were adjusted by cutting straight pipes under construction of the test specimen to make them work, and all the pipes were covered with the soil right after their placement. Therefore, a static loading test of PVC drainage pipe in the air was conducted to obtain more fundamental data, especially to see deformation behaviors including the straight portion of the drainage pipe.

Fig. 17 shows test setup and gage locations for the static loading test. The test specimen was a crank-shaped VU drainage with a reducing elbow and a lower elbow like Sections B to D in the shaking table test. The test specimen was pulled and pushed by using two turnbuckles and two pantograph jacks, respectively as shown in Figs. 18a and 18b. The specimen was instrumented with strain gages (Fig. 17b) in Sections a to e, two string pots and two load cells. To reproduce fixed condition at house foundation in the shaking table test, displacement-controlled loading was attempted by inputting identical displacement at both of the buckles or jacks. However, rotation could not be prohibited in this loading approach, and therefore, load-controlled loading was applied.

3.2 Deformation development of PVC drainage pipes in static loading test

Load-displacement curves at top and bottom loading points are plotted in Fig. 19a. The displacement at the top was always larger than at the bottom, and it indicates that the specimen at the loaded end were rotated. Figs. 19b to 19e show relationship between axial strain and input displacement averaged the displacements at

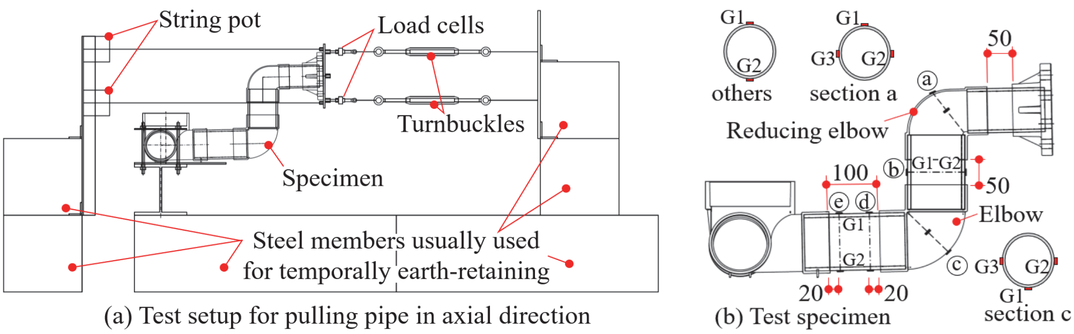

Fig. 17 – Dimensions of specimen and gage locations for static loading test

the top and the bottom string pots in Sections a to d. Strains in Section e showed identical tendency strains with in Section d. Based on the figure, the follows are drawn: 1) G1 gages along both of the elbow portions recorded insignificant axial strain. This tendency is similar to the results in the shaking table test. 2) The specimen was slightly less flexible at loading in pushing direction than in pulling direction as shown in Fig. 19c. It is probably because of its crank-shaped geometry of the PVC drainage. 3) Both sides of the reducing elbow are always in tension (G2 and G3 in Fig. 19b). These gages corresponded to RE-3 and RE-4 in the shaking table test and these gages also recorded compressive strain (refer to Fig. 9). It may result from bending due to the house slippage in X-direction in the shaking table test. In addition, the boundary condition at the house foundation may be another possible reason on the compressive strain.

Fig. 20 illustrates deformation shape of the PVC drainage specimen in the static loading test. Because actual PVC drainage pipes are usually embedded in the soil, they are less flexible due to confinement from the surrounding soil. Intensity of the confinement is related to the surrounding soil, and therefore, it should be noted that the most critical portion of the PVC drainage may be dependent on characteristics of the soil.

4. Conclusions

A series of shaking table test and a static loading test were performed to investigate deformation development and damage mechanisms of PVC drainage pipes. As a result, the following conclusions are drawn;

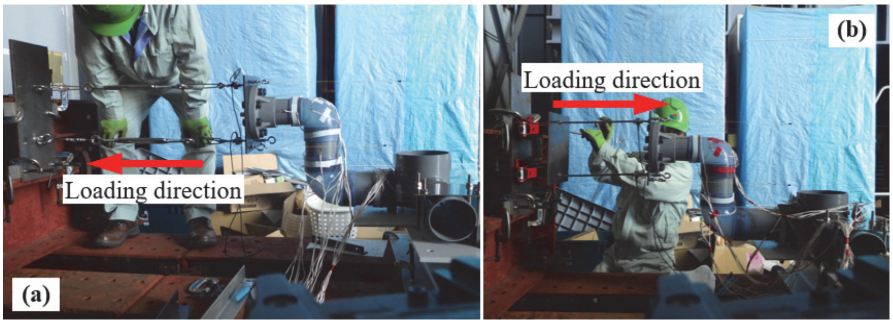

Fig. 18 – Test setup of static loading test in each direction

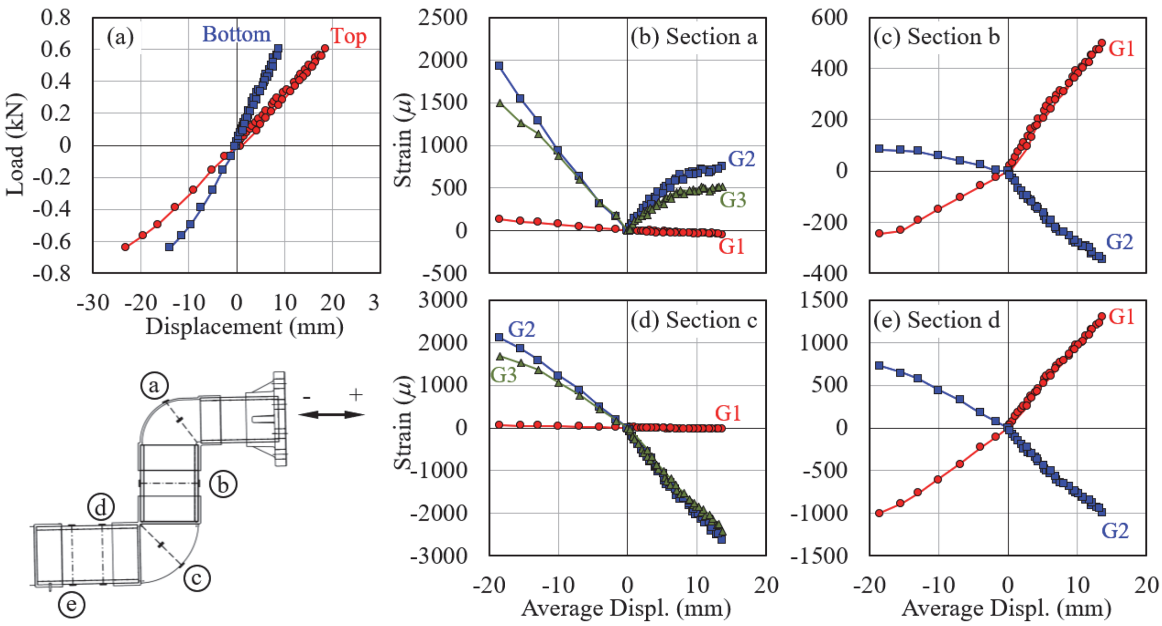

Fig. 19 – Behaviors of specimen at static loading in axial direction

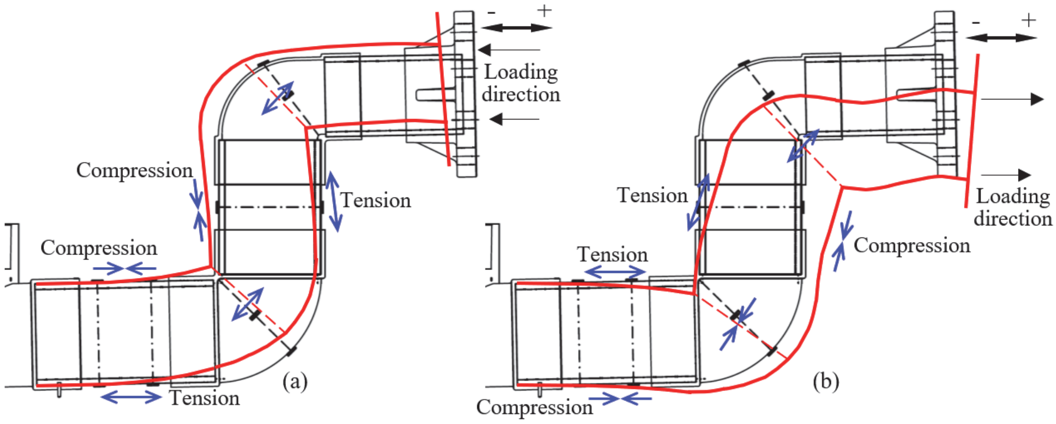

Fig. 20 – Deformation of PVC drainage at static loading in axial direction

1) Houses with high seismic performance tend to slip during strong motion. Because their slippage induces considerable relative displacement to PVC drainage pipes, the pipes may be fatally damaged. Seismic reinforcement can help controlling structural damage, but it should be noted that it may induce disorder of drainage function. This functional damage is highly related to significant reduction of city resiliency, and therefore, appropriate countermeasures need to be considered.
2) As a possible seismic reinforcement approach of PVC drainage pipe, a combination of a flexible pipe and expansion joints was applied in the shaking table test. Based on damage inspection, the reinforced pipe had considerable contraction along one of the expansion joints and pull-out of rubber packing, but it could avoid functional disorder. More modifications are necessary, especially against house slippage in pulling direction for the pipes.
3) Deformation and damage development of PVC drainage pipes are highly dependent on amount and direction of house slippage, fixity of pipes at house foundation, relative depth of embedment of pipes to house foundation, and their surrounding soil.

5. Acknowledgements

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