Cover page

Title: **On the use of steel pipe for crossing fault of flexure type in the Tama South-North line (tentative) development project**

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On the use of steel pipe for crossing fault of flexure type in the Tama South-North line (tentative) development project

Takeo Kitamura

ABTRACT

INTRODUCTION

Tokyo Waterworks Bureau is building a wide-area water transmission network in order to secure backup functions when facilities are being renewed, as well as when there are natural disasters or accidents. As part of this construction, the Bureau is building a large-scale water transmission pipe (φ 2,000, 15.6 km) in the Tama Area on the west side of Tokyo. In this project, after constructing a tunnel with an inner diameter of 2,750 mm using the shield method at depth of about 30 m below the ground, then the transmission pipes is supposed to be laid inside the tunnel, where there are parts crossed by the Tachikawa Fault.

In this paper, we report fault countermeasures studied in order to reliably maintain water flow function after an earthquake strikes, even in the parts crossed by the fault.

STUDY OF FAULT COUNTERMEASURES

In this construction project, the performance required in the event of an earthquake by the Bureau is seismic resistance 2 (limit state where water leaks do not occur even if ground is partially plasticized) as defined by the Waterworks Facility Seismic Resistance Guidelines (Japan Waterworks Association 2009). In addition, because the type of piping inside the tunnel must be cast iron pipes or steel pipes, we studied application of both types of pipe in the parts crossed by fault. In this study, we considered fault deformation based on the features of bending structures, clarified the required performance of countermeasures and control standards, performed 3D ground deformation analysis, and deformation analysis of each type of pipe with considering for fault location. As a result, we confirmed that both pipe types adequately satisfy performance requirements, so they can both secure safety against fault deformation. Based on this, for the selection of pipe types, we comprehensively evaluated workability, durability, construction period, previous track record and economic aspects etc., and finally we selected steel pipe and decided to use steel pipe for crossing fault for the location where a fault crosses and within 209m of area influenced by the fault.

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1. INTRODUCTION

Bureau of Waterworks, Tokyo Metropolitan Government is building a wide-area water transmission network in order to secure backup functions when facilities are being renewed, as well as when there are natural disasters or accidents. As part of this construction, the Bureau is building the Tama South-North Trunk Line (tentative name) on the west side of Tokyo. This water transmission trunk line involves using the shield construction technique to build a tunnel with an inner diameter of 2,750 mm at a depth. Of 30 m below the ground, stretching 15.6 km from Higashimurayama Water Purification Plant to Haijima Water Supply Station, then building a φ2000 large water transmission pipe inside the tunnel. This construction will make it possible to renovate and install seismic resistant joints on other water transmission pipes, and improve the stability of water supply to approximately 1.7 million people living in the western and southern parts of the Tama Area.

The active Tachikawa Fault runs through this construction area, so the Bureau has studied countermeasures to absorb fault displacement. In this paper, we report on a study case for the water transmission trunk line to be built in the section that the fault runs through.

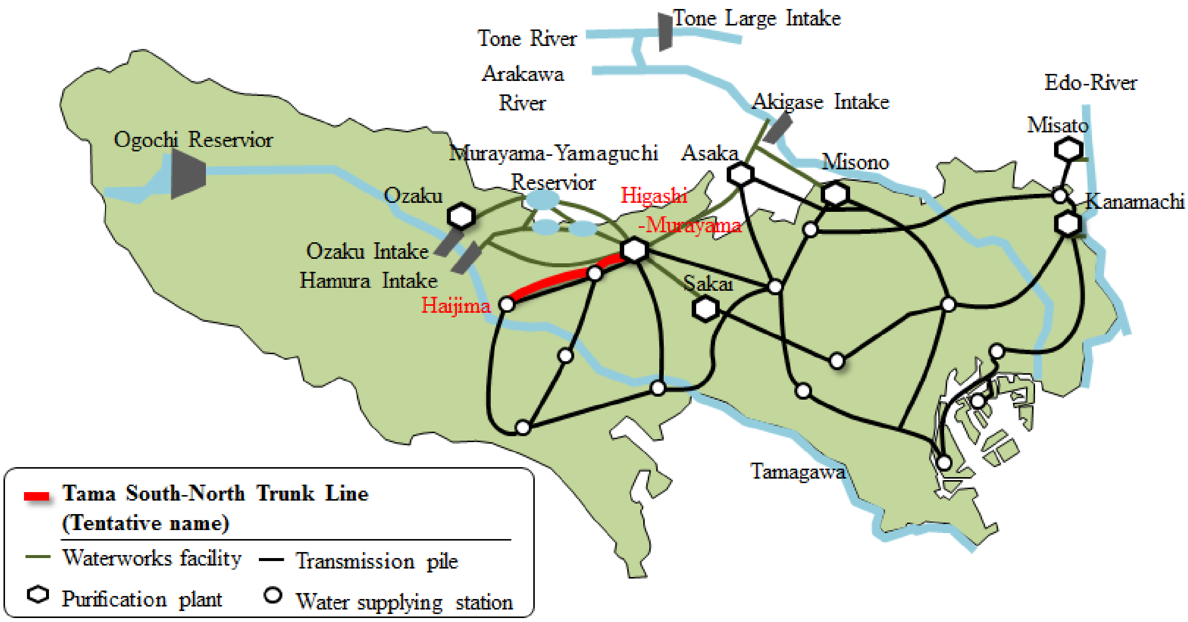

Figure 1: Major water supply facilities of the Tokyo Metropolitan Bureau of Waterworks

2. DETAILDS OF THE TACHIKAWA FAULT

The Tachikawa fault is a reverse active fault with its upper block on the east side. In the future, there is a 0.5% to 2% chance of an earthquake happening in the next 30 years, which places it in the group of faults with a relatively high chance of an earthquake happening among faults in Japan. Vertical sliding during fault activity is estimated to be 1.5 to 3.0. m. Despite the fact that it is a reverse fault, even if the fault slides very deep underground, it has a structure called flexure that will make the fault slide barely appear above ground. Known details of the Tachikawa Fault are shown in TABLE 1.

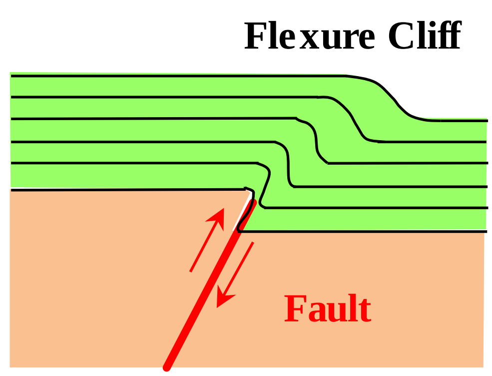

Figure 2: Image of a flexure structure (reverse fault)

TABLE 1. DETAILS OF THE TACHIKAWA FAULT

Category	"Certainty Level I" active fault (*The highest level of certaint that it is an active fault on a scale of I - III)
Activity	"B" (Average displacment veolicty: 25 - 30 cm per 1,000 years)
Length	21 - 22 km for the Tachikawa Fault alone (33 km Tachikawa Fault Zone including the Naguri Fault)
Location	From Iwakura, Ome-shi through Hakonegasaki, Mizuho-cho and Sunagawa, Tachikawa-shi, to Fuchu-shi
Direction, Gradient	From northeast to southeast. The fault has a very steep gradient of 60° to 90°.
Fault Displacement	Vertical displacement is 1.5 to 3.0 m each time, ratio vertical to lateral displacement is about 1:1. to 1:2 (no evidence of lateral displacement)
Fault Sense	Reverse fault with a surface bent up relative to the northeast side

3. SEISMIC RESISTANCE PERFORMANCE THAT MUST BE MAINTAINED

The Tama South-North Trunk Line (tentative name) will be built with a water transmission pipe inside a shield tunnel. When checking the seismic resistance, limit state of each waterworks facility had a minimum seismic resistance performance that must be maintained without water leaks according to the Waterworks Facility Seismic Resistance Guidelines (Japan Waterworks Association 2009), with inspection standards not to exceed the limit state of each part. The limit state of part for seismic resistance performance is as shown in TABLE 2.

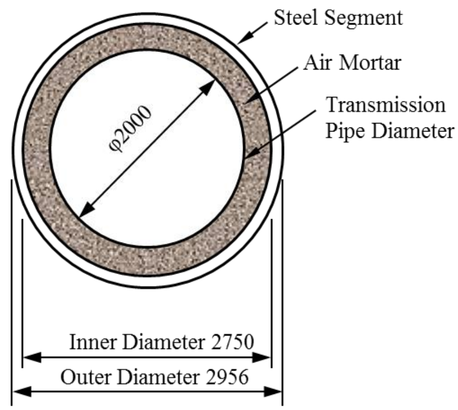

Figure 3: Standard Cross Section

TABLE 2. LIMIT CONDITION OF EACH MEMBER FOR SEISMIC PERFORMANCE

<table>
<tr><th>WW Facilities</th><th>Parts</th><th>Seismic Resistance 1</th><th>Seismic Resistance 2</th><th>Seismic Resistance 3</th></tr>
<tr><td rowspan="3">Buried Pipes</td><td>Pipes of Integral Pipeline</td><td rowspan="2">Limit state where dynamic characteristics do not exceed elastic range</td><td>Limit state where leaks do not occur even if there is partial plasticization</td><td>~</td></tr>
<tr><td>Pipes of jointed pipelines</td><td></td><td>~</td></tr>
<tr><td>Joints of jointed pipelines</td><td colspan="2">Limit state where joints do not leak</td><td>~</td></tr>
<tr><td rowspan="2">Shield Tunnel</td><td>Body</td><td rowspan="2">Limit state where dynamic characteristics do not exceed elastic range</td><td>Limit state where some parts are plasticized, but damage can be easily repaired</td><td>Limit state where damage can be repaired</td></tr>
<tr><td>Joints</td><td>Limit condition where even if some joints are broken, they can be easily repaired</td><td>Limit condition where even if some joints are broken, they can be repaired</td></tr>
</table>

In addition the required performance of shield tunnels and water pipes was set to have a rational and safe structure based on special conditions associated with a Tachikawa Fault earthquake: (1) if the Tachikawa Fault moves, a very large displacement of about 3 m will occur; (2) deformation will remain after the earthquake stops, (3) the pipes can be used without making repairs. (See TABLE 3)

(1) Water Transmission Pipes

The Tama North-South Trunk Line (tentative name) has been positioned as an important water supply facility. In the even that there is no alternative facility and it breaks down, the damages suffered would be enormous. Therefore, it is a Rank A1 of critical importance among water supply facilities, and must maintain Seismic Performance 2 in a Level 2 earthquake. However, in the time following an earthquake, it will be difficult to stop water flowing and make repairs, and depending on the type of pipe there may be a slight cross section compression, so fault countermeasures were chosen in consideration of the performance of such countermeasures in Japan so far. The type of piping used in the tunnel is either steel pipe or ductile cast iron pipe, in accordance with official standards (Water Pipe Design Guide 2011).

(2) Shield Tunnel

The shield tunnel will be laid about 30 m underground and will thus be difficult to repair if broken, so it was set to Seismic Performance 2. Although fault sliding causes limited damage, reference standards were set with required performance so that no major damage would be caused to waterworks even without making repairs.

TABLE 3. REQUIRED PERFORMANCE AND REFERENCE STANDARDS

Target Facility	Required Performance		Reference Standards		
	Seismic Res.	Limit State			
Water Main	Seismic Resistance 2	･Water tight seal can be ensured without joints coming loose or damage occuring ･Even with less fault cross-section area, water permeability is secured	Steel Pipe (straight part)		Tube Strain ≤ Allowable Strain
			Steel pipes for faults		Compressive displacement ≤ Allowable displacement Rotation angle ≤ Allowable rotation angle Flow cross section area after deformation ≥ Flow cross section area of straight pipe × 80%
			Ductile Cast Iron Pipe		Joint deformation ≤ Allowable deformation Joint bending angle ≤ Allowable bending angle Axial force generated ≤ Allowable axial force
Shield Tunnel	Seismic Resistance 2	･Load capacity of the segment ring does not decrease ･Water resistance of flexible segment is secured	Vertical	Steel Segment	Axial stress degree ≤ Limit stress degree
				Flexible Segment	Axial stress degree ≤ Limit stress degree
			Lateral	Segment Ring	Bending moment generated ≤ Tolerable ending stress Shear stress generated ≤ Tolerable shear stress
				Flexible Segment	Tensile force generated ≤ Tolerable tensile stress Shear stress generated ≤ Tolerable shear stress

4. STUDY ON THE IMPACT OF THE TACHIKAWA FAULT

(1) Test Calculations with 2D FEM

In this study, in order to first construct a ground deformation analysis model that reproduces the flexure structure characteristic of movement of the Tachikawa Fault, we recreated the flexure structure and did test calculations of fault deformation using a 2D FEM model assuming stratified ground. We also confirmed the applicability of shield tunnels and water transmission pipes as fault countermeasure construction methods with the response displacement method using the fault displacement calculated.

A) Simulation Analysis of the Present Conditions of the Ground

After applying dead weight to the FEM model of the ground without the tunnel and simulating the initial stress rate, we forcibly input the sliding caused by fault activity (fault angle 60°, vertical sliding 5 m, no lateral sliding) reported to have occurred in the past on the lower surface of the model. This confirmed the flexure structure of the ground surface in its present condition, in which the flex width is approximately 200 m when sliding vertically 5 m on the ground surface.

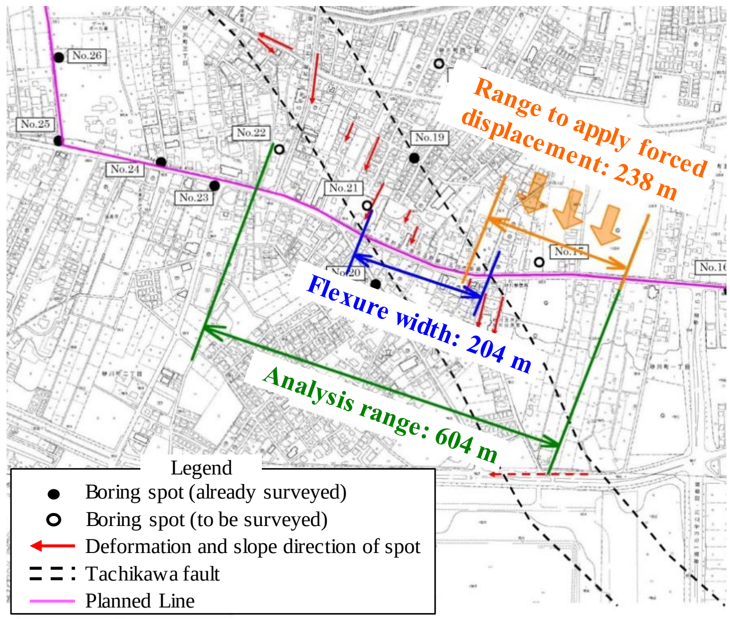

Figure 4: Range in which to analyze ground deformation

B) Fault Effect Analysis on the Ground Surface

Based on the existing material on the Tachikawa Fault and interviews with experts, we set CASE 1 assuming a reverse fault with the upper block on the east side and CASE 2 assuming a left lateral fault (See TABLE 4), then calculated fault displacement with 2D FEM.

TABLE 4. IMPACT ANALYSIS CASES

Case	Fault Angle	Vertical Displ.	Lateral Displ.	Comp. Displ.
CASE1 (Reverse Fault)	60°	3.0 m (Max)	–	3.0 m
CASE2 (Vert. & Lat. Fault)	80°	1.5 m	3.0 m (Max 1: 2)	3.4 m

At the tunnel position, there was vertical displacement of about 3 m in CASE 1 and 1.5 m in CASE 2, as well as pipe axial displacement of about 1.5 m in CASE 1 and about 2 m in CASE 2. Converting vertical displacement into angle, this equates to 0.9° in CASE 1 and 0.4° in CASE 2, with the result being that impact on the water transmission pipe is minimal.
However, in the study of fault countermeasures, because CASE 2 has a large pipe axial displacement, which will have a greater impact on the compression strain of the water pipe, we decided to use the fault displacement of CASE 2.

C) Study of Vertical Displacement of the Shield Tunnel and Water Transmission Pipe

There are two methods for examining the seismic resistance of shield tunnels and water pipes. The first method is to do FEM analysis of an integrated model of the ground and tunnel. The second is to do response displacement analysis of the tunnel and water transmission pipe models.

In this sort of situation, when considering seismic countermeasures for shield tunnels across faults, it is impossible to prevent major sliding displacement of the Tachikawa Fault, so it is more effective to absorb displacement with flexible joints using flexible segments or the like.

It is difficult to model flexible segments based on major deformation such as fault displacement or do modeling that incorporates shield tunnels and water transmission pipes that behave as one with those segments using FEM elements, so we modeled the tunnel and water pipes with beam elements and did analysis with the response displacement method using displacement due to fault sliding as an external force.

The results, as shown in TABLE 5, confirmed that both steel pipes and ductile cast iron pipes were effective as countermeasures against ground deformation when the Tachikawa Fault is active.

TABLE 5. SUMMARY OF TEST CALSULATIONS

Type of Pipe	Fault Countermeasures		Filler	Results of trial calculations	Comment
	Water Main	Flexible Segment			
Steel Pipe	Steel pipes for faults: 9 places	Compression Performance of 150 mm: 29 places	None	(1) Steel pipes for faults ・Compression displacement: 205 mm ≤ 368 mm PASS ・Rotation Angle: 0.10°≤ 12° PASS (2) Straight Pipe ・Strain: 0.2% ≤ 0.35% PASS	・Both the steel pipes for faults and straight pipes satisfy seismic safety requirements. ・Because there is no filler, there is a strong possibility that the water main and the tunnel will move separately and the two will come in contact.
	Steel pipes for faults: 9 places	Compression Performance of 150 mm: 29 places	Air milk with compression strength of $0.5N/mm^2$	(1) Steel pipes for faults ・Compression displacement: 443 mm ≤ 368 mm FAIL ・Rotation Angle: 0.33°≤ 12° PASS (2) Straight Pipe ・Strain: 0.12% ≤ 0.35% PASS	・Although the steel pipes for faults do not satisfy safety requirements at present, it is necessary to examin the potential to increase the allowable compression displacement to 450 mm or more by changing the specifications of the steel pipes for faults (Solved issue later through development). ・Air milk filling makes the water main and tunnel behave as one, there is no problem ith them contacting each other.
Ductile Cast Iron Pipe	Fault Section: 3 m pipe (200 m) Outside Fault Section: 5 m pipe	Compression Performance of 150 mm: 29 places	Air milk with compression strength of $0.5N/mm^2$	(1) Joint ・Compression Force: 2252 kN ≤ 5880 kN PASS ・Verification of overall expansion/contraction: Fault displacement 2 m ≤ 2.03 m (= 29 mm × 70 pipes) ・Rotation Angle:0.35°≤ 1.83° PASS (2) Straight Pipe ・Stress: 16 N/mm2 ≤ 270 N/mm2 PASS	・Ductile cast iron pipes satisfy seismic safety requirements. ・Air milk filling makes the ductile pipe and tunnel behave as one, there is no problem ith them contacting each other.

(2) 3D Ground Deformation Analysis Simulation

Based on the results of 2D FEM analysis and ground survey results conducted separately, we constructed a 3D FEM model by modeling the strata structure in the area where the pipeline crosses the Tachikawa Fault, and analyzed ground deformation when the fault is active with either vertical sliding or lateral sliding.

A) 3D FEM Model

The range of analysis for calculating ground displacement due to the impact of the fault is shown in Figure 5. Flexure width of the Tachikawa Fault is set to a width of 200 m for faults FW-FE which have an active fault certainty of medium, centered on faults F-C which have an active fault certainty of high. The range of analysis in the horizontal direction is based on the 2D results, with flexure width at the center and 200 m added in both the east and west directions (wide enough that fault movement does not impact the borders), totaling 600 m.

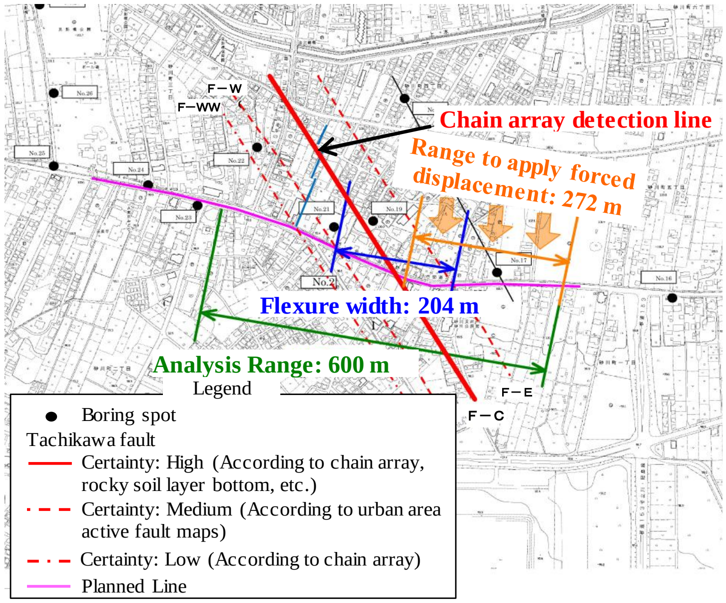

Figure 5: Analysis range to calculate ground deformation caused by faults

The FEM analysis model is shown in Figure 6. We made adjustments in the 3D FEM model so that the horizontal input range of forced displacement (range of 272 m east of the vicinity of faults F-C) and the vertical analysis range (64 m) fit the flexure width of the ground surface (approximately 200 m).

We set width in the 3D depth direction to 20 m, and the nodes in the boundary positions facing each other in the depth direction in the program to have the same displacement. That is to say, we set infinite width in the depth direction. See TABLE 4 for impact analysis cases.

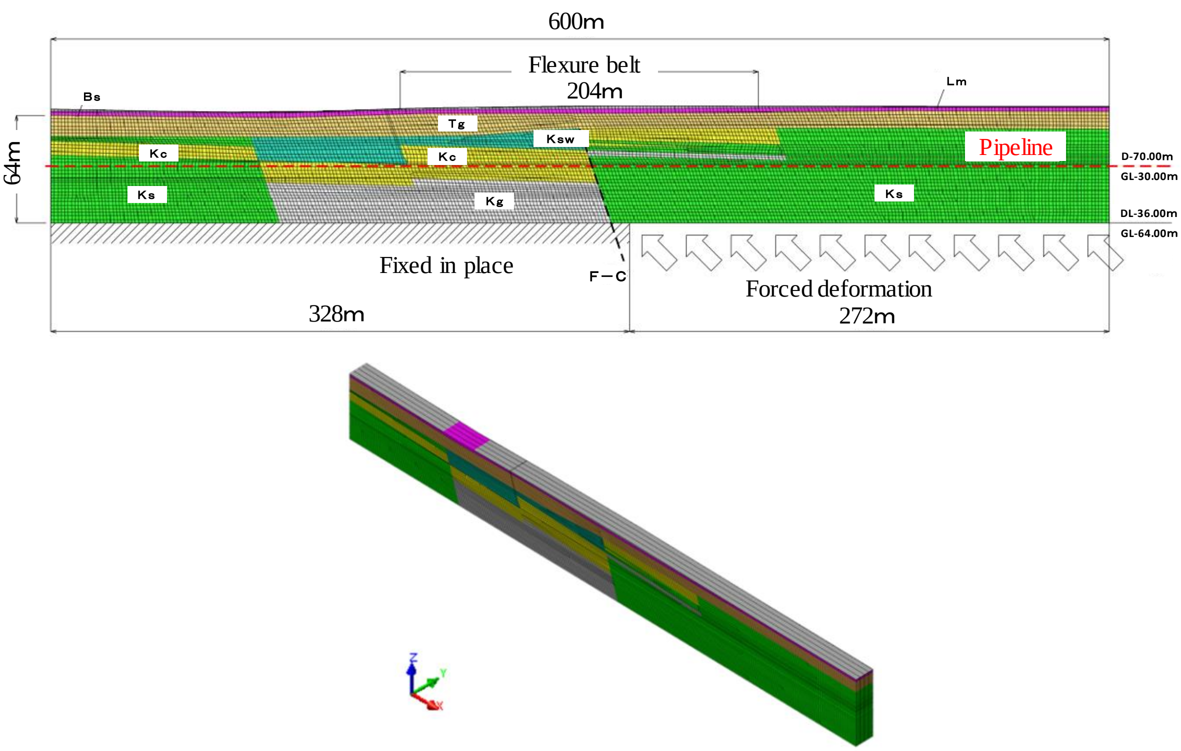

Figure 6: Analysis Model

B) Analysis Results of Fault Displacement

The fault displacement distribution contour and tunnel position ground displacement distribution (3D FEM) are shown in Figures 7 and 8. In the distribution graph, we also shown the 2D FEM ground displacement for reference. The actual fault plane obtained in ground surveys is modeled in the 3D FEM analysis, with forced displacement applied near the fault plane. For this reason, vertical ground displacement at the tunnel position was larger than that in the 2D FEM analysis.

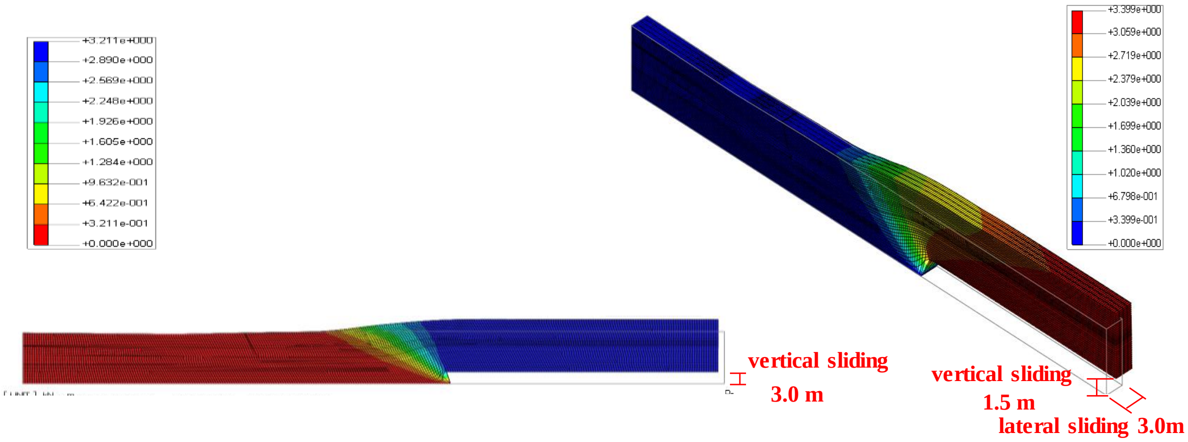

Figure 7: Fault Displacement Contours

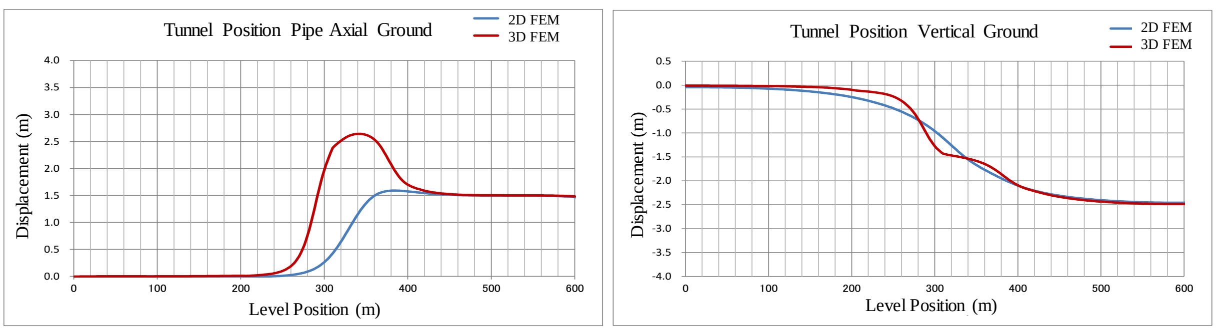

Figure 8: Distribution of ground variation

C) *Evaluation of Impact on Shield Tunnels and Water Transmission Pipes*

We built a 3D framework model of the shield tunnel and water transmission pipe, conducted response displacement analysis using the ground deformation when the fault is active calculated in B), and studied the impact on the shield tunnel and water transmission pipe.

1) Arrangement of steel pipes for faults and flexible segments
○Steel pipes for faults
[Structure]
By installing easily deformed chevron parts (buckling corrugated part) in advance, these steel water pipes can ensure that water keeps flowing without any cracking or water leaks from the pipe, even when subjected to forced displacement of about 60 cm in each location. Their use is specified in WSP 077-2012 "Steel Pipes for Faults" (See Figure 9).

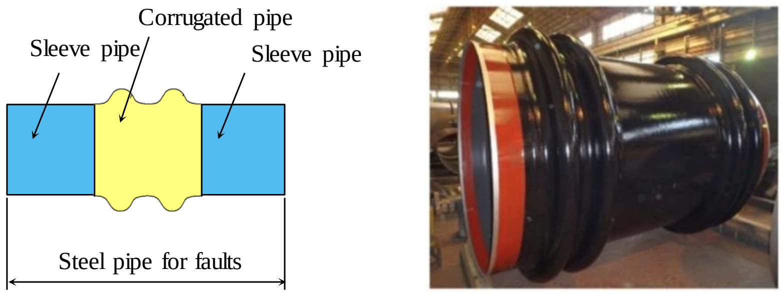

Figure 9: Steel pipes for faults

[Mechanism of fault displacement absorption]

By absorbing deformation, the easily deformed chevron parts (buckling corrugated part) follows the large fault displacement (See Figure 10).

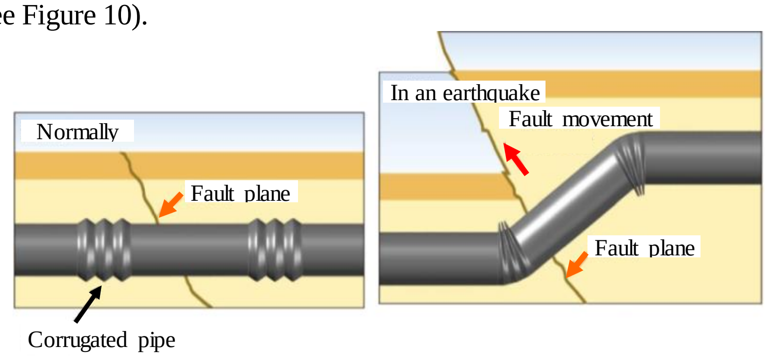

Figure 10: Fault displacement mechanism

[Arrangement]

In consideration of the ground strain in CASE 1 and CASE 2, we set the shared strain of each corrugated part was based on the allowable compression displacement of the steel pipe for faults, and determined the arrangement of the steel pipes for faults and flexible segments (Figure 11).

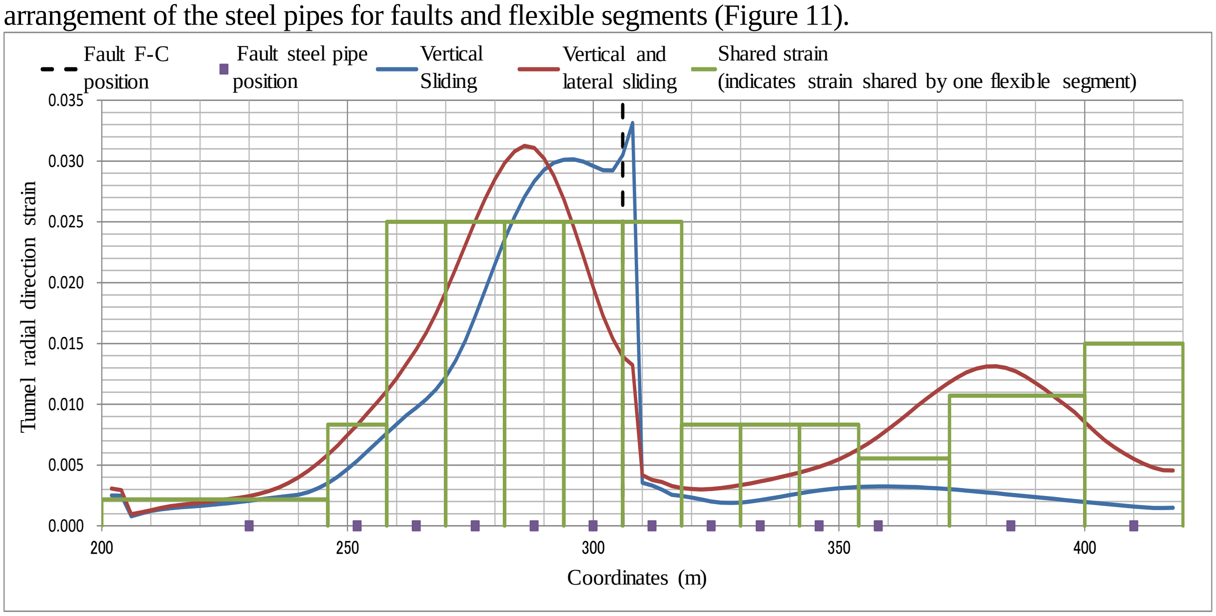

Figure 11: Arrangement of steel pipes for faults

2) Arrangement ductile cast iron pipes and flexible segments

○US ductile cast iron pipes

[Structure]

These cast-iron pipes (see Figure 12) have seismic resistant joints that can expand and contract, are flexible, and have a detachment prevention function. By installing long joint rings, it is possible to increase the allowable expansion and contraction of the pipeline. (See Figure 13).

It is possible to build an optimal seismic resistant pipeline according to the degree of ground displacement (major displacement response pipeline system) by combining existing products, such as by shortening the pipeline in this section according to the degree of ground displacement, and arranging long joint rings on both sides of the section.

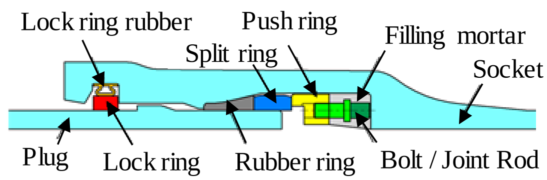

Figure 12: US Ductile Cast Iron Pipe

[Mechanism of fault displacement absorption]

Even if deformation occurs in one joint, adjacent joints move one after another and long joint rings absorb major deformation, following large fault displacements. Even if tension, compression, and bending displacement occur, the joints also move so stress on the pipeline is alleviated.

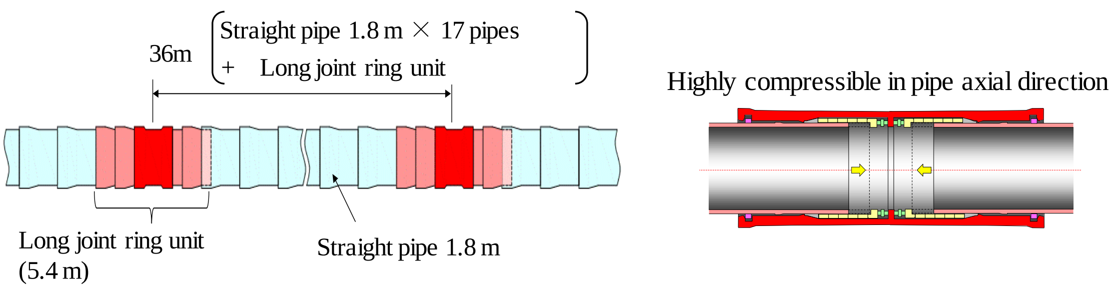

Figure 13: Major displacement pipeline system with long joint ring units

[Arrangement]

In order to cope with fault displacement in CASE 1 and CASE 2, we applied a major displacement pipeline system that combines long joint ring units and short pipes to the ductile cast iron pipes, and arranged piping to absorb ground displacement. We also determined the arrangement of flexible segments so that they follow fault displacement (See Figure 14).

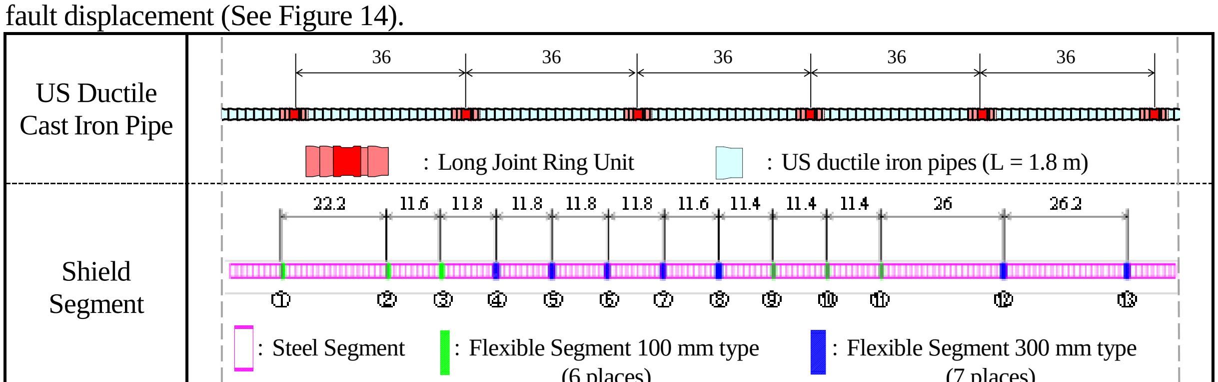

Figure 14: Arrangement of US ductile cast iron pipes and shield segments

3) Analysis results of ground deformation in the flexure structure

As shown in TABLE 6, we confirmed that in CASE 1 (reverse fault) and CASE 2 (vertical and lateral sliding fault), both the steel pipes for faults (13 places) and ductile cast iron pipes (major displacement response pipeline system using long joint units) were within the reference standards for each item, and serve as effective countermeasures against the impact of the Tachikawa Fault.

TABLE 6. ANALYSIS RESULTS FOR GROUNND DISPLACEMENT IN THE FLEXURE STRUCTURE

Slippage	Target Facility	Fault Counter Measures	Study Results			
CASE 1 Reverse Fault	Water Main	Fault Countermeasure Steel pipes for faults: 13 places	Waveform Part	Comp. Displacement	300 mm ≤ 320 mm	PASS
				Bending Angle	2.32° ≤ 16°	PASS
				Flow Cross-Section	The bending angle is small and does not affect. The water flow (secured 80% or more)	PASS
			Straight Part	Strain	0.15% ≤ 0.34%	PASS
	Shield Tunnel	Flexible Segments: 13 places	Vertical	Steel Segment	Stress: 406 N/mm^2 ≤ 490 N/mm^2	PASS
				Flexible Segment	Using a product within the cross-section generated, the segment does not break	PASS
	Water Main	Ductile cast iron pipes using long joint unit (major displacement pipe system)	Joint Deformation		36 mm ≤ 310 mm	PASS
			Joint Bending Angle		1.64° ≤ 5.9°	PASS
			Axial Force Generated		5927 kN ≤ 6000 kN	PASS
	Shield Tunnel	Flexible Segments: 13 places	Vertical	Steel Segment	Stress: 120 N/mm^2 ≤ 490 N/mm^2	PASS
				Flexible Segment	Using a product within the cross-section generated,the segment does not break	PASS
CASE 2 Vertical & Lateral Fault CASE 2	Water Main	Fault Countermeasure Steel pipes for faults: 13 places	Waveform Part	Comp. Displacement	300 mm ≤ 320 mm	PASS
				Bending Angle	0.84° ≤ 16°	PASS
				Flow Cross-Section	The bending angle is small and does not affect. The water flow (secured 80% or more)	PASS
			Straight Part	Strain	0.12% ≤ 0.34%	PASS
	Shield Tunnel	Flexible Segments: 13 places	Vertical	Steel Segment	Stress: 345 N/mm^2 ≤ 490 N/mm^2	PASS
				Flexible Segment	Using a product within the cross-section generated, the segment does not break	PASS
	Water Main	Ductile cast iron pipes using long joint unit (major displacement pipe system)	Joint Deformation		79 mm ≤ 310 mm	PASS
			Joint Bending Angle		1.52° ≤ 5.9°	PASS
			Axial Force Generated		5852 kN ≤ 6000 kN	PASS
	Shield Tunnel	Flexible Segments: 13 places	Vertical	Steel Segment	Stress: 140 N/mm^2 ≤ 490 N/mm^2	PASS
				Flexible Segment	Using a product within the cross-section generated, the segment does not break	PASS

5. SELECTION OF COUNTERMEASURE CONSTRUCTION METHOD

Both steel pipes for faults and ductile cast iron pipes (major displacement pipeline system using long joint rings) have comparable performance, so we conducted a comparative study in order to select a construction method.

When selecting the type of pipe, we compared safety, workability, roadside environment, and construction period, but both types of pipe were comparable, so we studied the type of pipe to use in the Tachikawa Fault section by evaluating economic efficiency. Steel pipes were found to be more economically efficient, so we decided to use flexure-proof steel pipes for faults.

TABLE 7. COMPARISON OF TYPES OF PIPE

		Steel pipes for faults	US Ductile Cast Iron Pipe
Safety	Flammable gas countermeasures	･There is no danger of explosions ･Evacuate to both shafts in case of fire	･There is no work that causes explosions
Workability	Pipe branch, gradient, bending	･(Distance) Power suply for welding machines can be dealt with by installing transformers inside pipes	･No problem with branches, distance, gradient, bending
	Fault support (See notes)	･Can be supported with steel pipes for faults	･Can be supported with special piping (long join rings, etc.)
Roadside Environment	Smoke countermeasures, ventilation measures	･Can be supported by installing large dust collectors ･Soundproof house was installed in the shafts	･There is no need for smoke countermeasures ･Soundproof house was installed in the shafts
Construction Period		○	○
Economic Efficiency		◎	○

6. CONCLUSION

This example is a study conducted underneath an engineering foundation, and normally would not require seismic resistant design to protect against earthquakes. However, construction will be done in a special environment crossed by the Tachikawa Fault. In preparation for an earthquake directly beneath the Tokyo area expected to strike in the next few decades, the Bureau enacted seismic countermeasures and utilized the first anti-bending steel pipes for faults in Japan. In order to secure a stable water supply of 13.4 million people in Tokyo, the Tokyo Metropolitan Bureau of Waterworks will continue to prepare for disasters by building this kind of strong facility.